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NAVAL CIVIL ENGINEERING LAB PORT HUENEME CA C KEENEY
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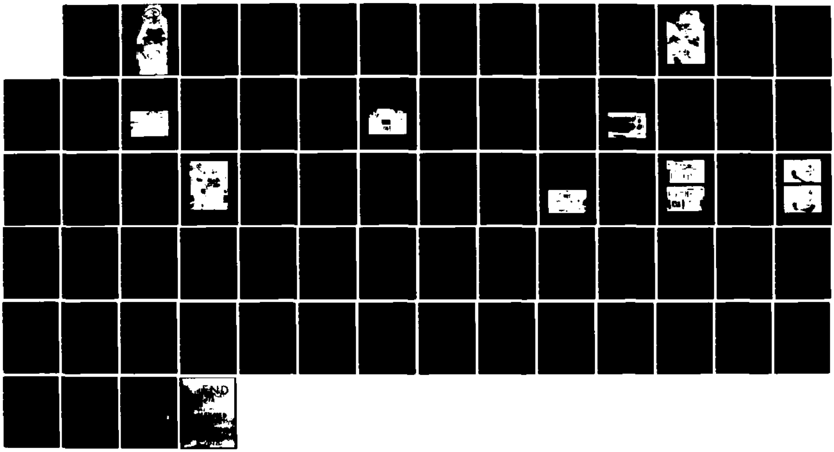

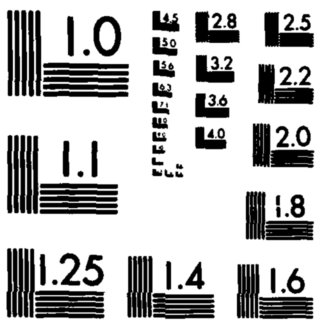

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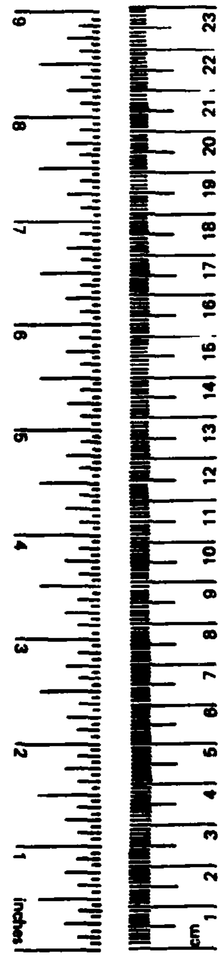
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

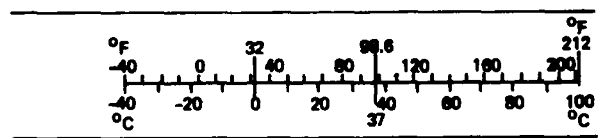
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2,000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1,000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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The inspection, maintenance, and repair of waterfront facilities require an efficient method of removing marine fouling and corrosion from underwater structures. In 1979 and 1980, the Naval Civil Engineering Laboratory (NCEL) conducted an evaluation of commercially available methods of underwater surface cleaning on waterfront structures. Based upon the results of the tests, it was concluded that no single system possessed the necessary combination of safety and operational characteristics needed to meet the Navy's

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waterfront structure cleaning requirements. Therefore, in 1981 a prototype high-pressure waterjet cleaning system was developed that incorporated the best features identified during the commercial system evaluations. In 1982 and 1983 the prototype waterjet cleaning system was tested, modified, and field-evaluated. It was determined that the high-pressure waterblaster was best-suited for cleaning steel underwater structures, particularly in limited access areas, while on concrete underwater structures, the best cleaning tool was found to be the Whirl Away rotary abrading hydraulic tool. Both concrete and steel underwater structures can be effectively and efficiently cleaned using the NCEL system, since one power source can drive both the Whirl Away hydraulic tool and the NCEL waterjet pistol.

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A PROTOTYPE HIGH PRESSURE WATERJET CLEANING SYSTEM
(Final), by C. Keeney

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1. Underwater cleaning   2. Waterfront facilities   I. YO995-01-004-310

The inspection, maintenance, and repair of waterfront facilities require an efficient method of removing marine fouling and corrosion from underwater structures. In 1979 and 1980, the Naval Civil Engineering Laboratory (NCEL) conducted an evaluation of commercially available methods of underwater surface cleaning on waterfront structures. Based upon the results of the tests, it was concluded that no single system possessed the necessary combination of safety and operational characteristics needed to meet the Navy's waterfront structure cleaning requirements. Therefore, in 1981 a prototype high-pressure waterjet cleaning system was developed that incorporated the best features identified during the commercial system evaluations. In 1982 and 1983 the prototype waterjet cleaning system was tested, modified, and field-evaluated. It was determined that the high-pressure waterblaster was best-suited for cleaning steel underwater structures, particularly in limited access areas, while on concrete underwater structures, the best cleaning tool was found to be the Whirl Away rotary abrading hydraulic tool. Both concrete and steel underwater structures can be effectively and efficiently cleaned using the NCEL system, since one power source can drive both the Whirl Away hydraulic tool and the NCEL waterjet pistol.

CONTENTS

INTRODUCTION

The inspection, maintenance, and repair of waterfront facilities require an efficient method of removing marine fouling and corrosion from underwater structures. Presently over half of the Navy's dive time required for underwater maintenance and repair is spent cleaning a structure before the actual work is begun. Improved methods of underwater surface cleaning are needed to decrease this surface preparation time.

The development and recent widespread use of high-pressure waterjets have provided a means of quickly and effectively cleaning offshore structures. With the use of waterjet devices, divers have obtained higher cleaning rates, decreased work time, and improved ability to clean complex nodes and shapes that are inaccessible with conventional cleaning tools. As more diver safety features have been incorporated into high-pressure waterjet systems, this method of underwater surface cleaning has increased in use. The numerous waterjetting systems available vary in design, operation, and efficiency. In 1979 and 1980, the Naval Civil Engineering Laboratory (NCEL), under the sponsorship of the Naval Facilities Engineering Command (NAVFAC), conducted an evaluation of commercially available methods of underwater surface cleaning on waterfront structures.

Based upon the results of the tests, it was concluded that there was no commercial system available that combined the best safety and operational characteristics to meet the Navy's waterfront structure cleaning requirements. Therefore, in 1981 a prototype high-pressure waterjet cleaning system was developed that incorporated the best features identified during the commercial systems evaluation. In 1982 and 1983 the NCEL prototype waterjet cleaning system was tested, modified, and field evaluated. This Technical Report presents the results of the NCEL cleaning system development effort.

EVALUATION OF COMMERCIAL CLEANING SYSTEMS

Objective And Criteria

During 1979 and 1980, several commercially available underwater cleaning systems were evaluated to identify improved cleaning techniques to decrease the Navy dive time required for surface preparation. The objective of the cleaning tests was to determine the characteristics and capabilities of currently available underwater cleaning devices for removing marine fouling from submerged concrete, steel, and timber waterfront structures. These characteristics could be used, along with other selection criteria, to choose an appropriate commercially available cleaning system for a particular Navy application.

Selection criteria included the following:

- diver safety
- ease of use
- performance
- efficiency and cost

Descriptions Of Systems

Nine underwater surface cleaning tools were evaluated. Seven were waterjet devices that utilized cavitating fan jets, very-high-pressure fan or straight jets, and/or abrasive injection. The mechanical cleaning devices included a rotary abrading tool with 49 hardened steel blades that attaches to a standard hydraulic drill, grinder, or sander, and a hydraulic chipping hammer. The waterjet systems selected for capabilities testing were typical of the range of currently available equipment. Table 1 summarizes the types of waterblaster cleaning systems evaluated.

Results

The performance of the equipment depended upon the following parameters:

- diver experience and familiarity with the equipment
- operator technique
- equipment design and capabilities
- type and amount of fouling

As the tests progressed, it became apparent that the divers with experience in handling high-pressure jets and underwater cleaning operations achieved higher cleaning rates. The final surface condition and cleaning rate also depended upon the technique the diver used in operating the equipment. The distance from the work surface, the angle between the surface and the waterjet, and the rate of translation of the tool over the surface are other important factors that influenced the final results. Often, the operator did not maintain the standoff distance or impingement angle recommended by the tool manufacturer. Also, to ensure complete and thorough cleaning of the surface, the operator tended to retrace previously cleaned areas or to move slowly across the work surface. It was determined that the best general operating technique for all the tools included a standoff distance of 1/2 to 3 inches, an impingement angle of 50 to 90 degrees, and quick and agitated translation. Each tool has an optimum operating technique that should be established prior to any actual cleaning.

Table 1. Summary of Commercial Waterblaster Cleaning Systems Evaluated

Waterblaster Type	Nozzle		
	Description	Pressure (psi)	Flow
Dump-valve waterjet pistol; no counterthrust	Interchangeable cavitating fan jet nozzles	10,000	2-3 gpm
Dump-valve waterjet gun with adjustable retrojet	Cavitating fan jet nozzle	3,000	22 gpm
Dump-valve waterjet gun with adjustable educted retrojet	Cavitating fan jet nozzle	3,000	18 gpm
Pilot-operated waterjet gun with diffuser shrouded retrojet[a]	Interchangeable noncavitating fan jet nozzles	4,000-10,000	26-14 gpm
Abrasives delivered through separate "dry" line. Retrojet with diffuser shroud on pilot-operated gun[a]	Interchangeable noncavitating fan jet nozzles	6,000 (water) 140 (grit)	20 gpm (water) 50 cfm (grit)
Dump-valve shoulder stockgun; no counterthrust	Interchangeable noncavitating fan jet nozzles	4,000-10,000	7-10 gpm
Dump-valve waterjet pistol; no counterthrust	Interchangeable noncavitating fan jet nozzles	10,000	2-3 gpm

[a]These waterblasters were the only tools tested that did not utilize a bypass or dump valve on the gun. These recirculated flow at the pump and shut off all flow to the tool whenever the trigger was released.

The design of the equipment and its ease of use also affected the overall performance and cleaning rate. The heavier and larger equipment was more difficult to maneuver and handle. This was also true with rigid, high-pressure hoses. The devices without retrojets and with highly tensioned triggers tended to cause early diver fatigue, especially in the hands and arms.

The structures that were more densely covered with shell growth, such as barnacles and tubeworms and other heavy fouling, took the longest to clean, as would be expected. The concrete surfaces tended to be fouled with more tenacious and adherent calcareous growth, which required more time and energy to clean than the steel surfaces.

The counterthrusted high-pressure water gun cleaned steel surfaces the most effectively, averaging cleaning rates of over 4 ft^2/min. However, the grit injection gun was the only tool that cleaned steel to a bare metal finish. The rotary abrading tool was the most effective and easiest to use on concrete structures. A low pressure created by the rotating blades helped to support the tool against the work surface. The cavitating waterjet pistol was the easiest waterblaster to use because of its size and weight. The diver did not report any early fatigue from the 7- to 8-pound reaction force and could operate the tool with one hand.

Recommendations

Based upon the results of the cleaning tests, the following types of commercially available devices were recommended for cleaning underwater structures:

- a reactionless waterjet with variable flow rates and pressures for accessible, heavily fouled concrete and steel structures
- a sand injection waterjet to remove all protective coatings from steel surfaces, leaving a bare metal finish
- a rotary abrading device for concrete structures that are easily accessible (Figure 1)
- a cavitation pistol in limited access areas and for routine cleaning of concrete and steel structures

It was also recommended that all high-pressure waterjet cleaning systems include an on-off safety lock, a trigger guard, and at least one length of lightweight, flexible, high-pressure supply hose to improve diver safety and ease of use.

No single commercial system, however, met the Navy's specific waterfront structure cleaning requirements. Therefore, a need still existed for an improved high-pressure waterjet cleaning system that incorporated optimized safety and design features to meet these Navy requirements. The commercial cleaning systems test and evaluation are described in detail in Reference 1.

Figure 1. Whirl Away rotary abrading tool.

PROTOTYPE DEVELOPMENT

Specifications

High-pressure waterjet systems usually require large amounts of power to develop the proper operating pressures and flow rates. Many cleaning systems are counterbalanced to produce no net thrust on the diver and, therefore, lose over 50% of the potential cleaning power developed at the pump in the retrojet nozzle alone. Underwater cleaning efficiency can be enhanced by fluctuating stresses from the collapse of cavitation bubbles on the surface being cleaned. The cavitation bubbles occur at the nozzle exit due to the high relative velocity between the exit jet and the stationary ambient fluid.

High-pressure waterjetting is a potentially hazardous operation. The risks increase when the operator is subjected to the underwater conditions of poor visibility and cold temperatures. Therefore, waterjet systems utilize a variety of different safety features to decrease the potential dangers encountered when operating these devices submerged in a marine environment.

Considering the above observations, a small, hand-held, high-pressure pistol that does not require any thrust compensation and utilizes cavitation erosion was selected as the best underwater surface cleaning device for Navy applications based upon efficiency, ease of use, safety, and capability. The cleaning system also included a diesel-driven power source and all interconnecting hoses and hardware. Based upon the results of the commercial systems evaluation, specifications for the prototype cleaning system were developed and are listed in Table 2.

Table 2. Original Contract Specifications

Item	Specification
Cavitating Waterjet Pistol	
Operating Depth	120 ft
Pistol Weight	5 lb maximum weight (in water)
Jet Thrust	12 lb maximum
Design Safety Factor	2:1 minimum
Trigger Mechanism	Operable by diver wearing three-fingered gloves 10-lb maximum actuating force 5-lb minimum actuating force Lock-open switch in no-flow position Positive shutoff of high-pressure water at pistol

continued

Table 2. Continued

Item	Specification
Nozzle Type	Cavitating straight and fan jet Cavitation focused within 1/2 to 2 in. from nozzle
Nozzle Pressure	10,000 psi
Nozzle Flow Rate	2-3 gpm
Noise Level	Below 8-hr OSHA standard when measured through 1/2-in. wetsuit hood
Power Unit	
Dimensions	2 x 5 x 2-1/2 ft[a]
Weight	1,700 lb maximum[a]
Frame	Adaptable for crane and forklift handling
Pump	Positive displacement
Power Source	Air-cooled diesel 8-hr fuel supply Fuel-level gage 12-V starter Heavy-duty battery
Hose Storage	Rack or hand-powered reel
Interconnecting Hardware	
High-Pressure Hose	Three 50-ft, 5/16-in. ID hoses
Foot-Actuated On-Off Valve	Controls high-pressure water flow from power unit to tool Automatic direct shutoff of high-pressure water Uniform port sizes or adapters for uniform port sizes
Gages	Engine hour meter Engine oil pressure Pump pressure Unloader pressure level
Water Reservoir	Sized to provide 10 min of uninterrupted operation[a] 1-1/2-in. NPT threads for water inlet

[a]These values are considered design goals and not absolute parameters.

Contract Performance

A contract was awarded to Flow Industries, Inc., Kent, Wash., to develop the prototype underwater cleaning system. The contractor was required to develop preliminary and final designs and then to fabricate, test, and deliver a complete underwater surface cleaning system.

The approach proposed by Flow Industries, Inc. during the preliminary design review utilized a pressure intensifier pumping unit to supply 10,000-psi water to the cleaning tool. Advantages of the intensifier pump for this application over the more common triplex pump include the following:

- The intensifier can be used to supply several cleaning tools simultaneously. The number of tools that can be supplied by a single unit is limited only by available horsepower.

- The intensifier is hydraulically driven by a pressure-compensated pump. This permits direct tool shutoff (i.e., no high-pressure water bypass is required).

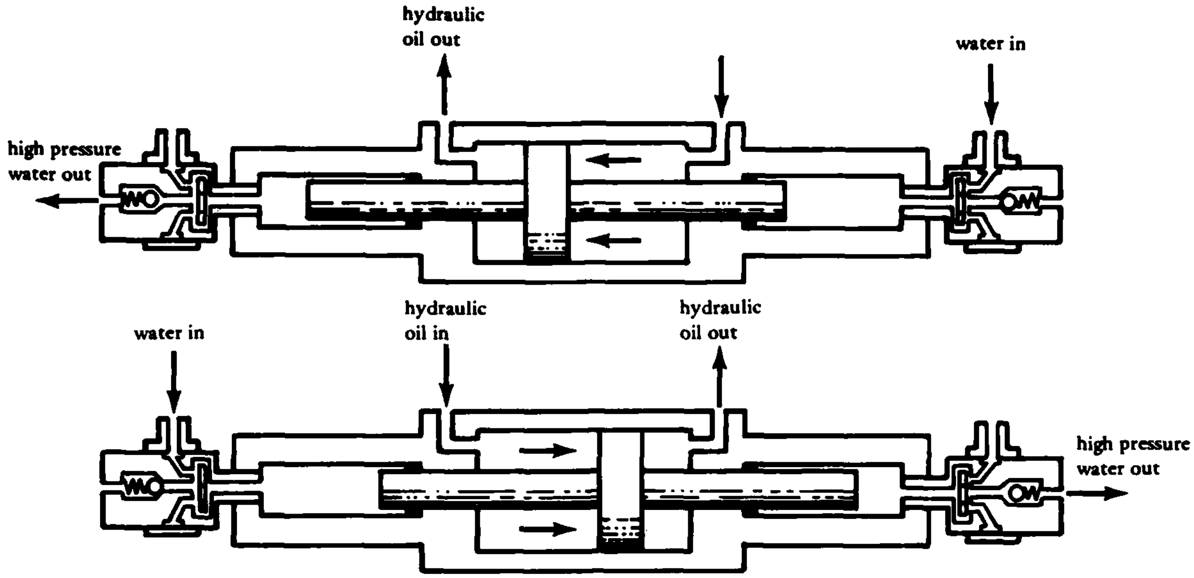
- Intensifier output flow rate and pressure are directly controlled by demand. This feature contributes to fuel conservation when the system is either idling or operating at less than peak demand.

- The intensifier is compact, reliable, and easily serviced and maintained.

The high-pressure, double-acting fluid intensifier is a hydraulically driven, reciprocating plunger pump (Figure 2). Pressurized hydraulic oil is valved to alternate sides of a large piston, causing it to move back and forth. The large piston is connected to two smaller pistons that pump water on each stroke. The relationship between oil pressure and water pressure is determined by the 4:1 ratio of the oil piston area to the water piston area. Thus, when the hydraulic oil pressure is 2,500 psi, the resulting water pressure will be 10,000 psi.

Two trigger valve designs for the waterjet cleaning tool were presented during the preliminary design review. The first design used a pneumatic system to indirectly actuate and stop the high-pressure water flow (Ref 2). The disadvantage of the pneumatic control was its slow response time. It was estimated that there would be up to a 1-second delay in completely stopping all flow from exiting the nozzle.

The second preliminary trigger valve design employed a direct shutoff with a spring-loaded mechanical valve stem. This design provided a positive method for controlling the high-pressure water with no delay in response time. However, it was decided that tool performance and reliability would improve with a pilot-operated trigger valve to directly control the flow and decrease diver fatigue by decreasing the hand force required to maintain the trigger in the full open position.



Operating Principal of Double Acting Fluid Intensifier

General Specifications

Weight – 97 lb
Water Flow Required
Submerged – Pumps from surroundings
Not Submerged – 10 gpm at 40 psi
Water Filtration Required – 1 μ
Oil Filtration Required – 25 μ

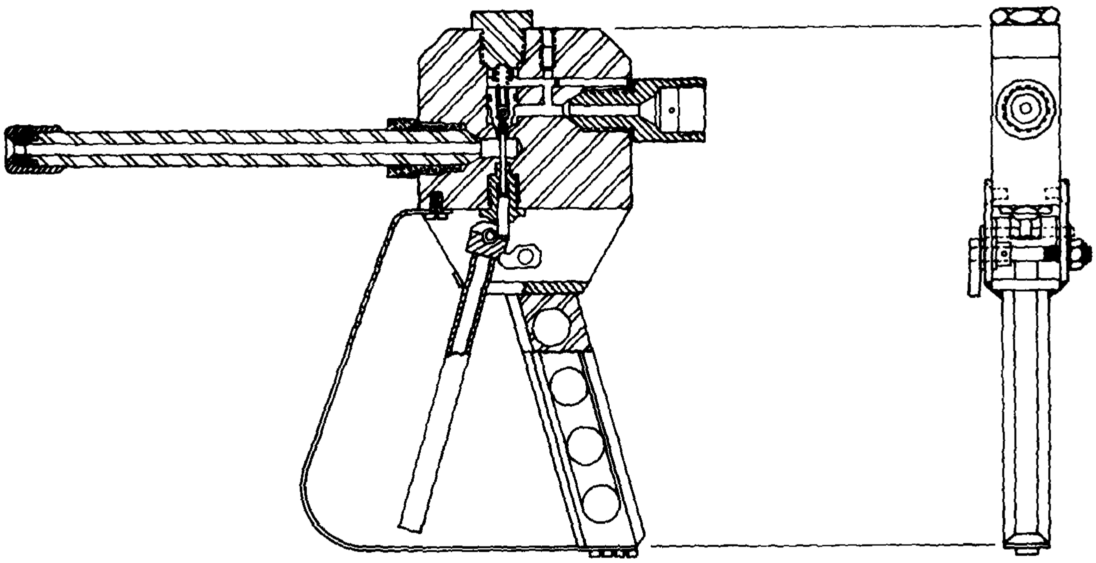
Oil Input Required – 24 gpm at 3,000 psi
(maximum operation)
Output Water Pressure – 12,000 psi
(maximum working pressure)
Oil Type Required – Shell Tellus 68
or Equivalent

Figure 2. Flow Industries, Inc. double-acting fluid intensifier (from Ref 2).

During the preliminary design review the specification for a water reservoir was waived and replaced by an auxiliary or "charge" water pump to supply a minimum of 50 psi to the pressure intensifier. It was also agreed that overall system performance would be improved by using a single-size, 5/16-inch-ID, high-pressure supply hose instead of the specified 1/2-inch- and 1/4-inch-ID hose combination. The selected Polyflex 2000ST hose provides uniformity of fittings and connections and causes a smaller pressure drop while maintaining flexibility. These modifications to the original specifications were included in the final design. A detailed description of the contract prototype development can be found in Reference 2.

As-Built System Description

Cleaning Tool. The cleaning tool is a cavitating waterjet pistol (Figure 3) designed for one-hand operation. High-pressure water flow through the tool is controlled by differential pressure on a poppet valve (Figure 4). The small-diameter pilot valve is manually controlled by the pistol trigger. Depressing the trigger forces the pilot valve from its seat and allows high-pressure water to flow to the nozzle and balance the pressure on the main poppet valve. Hydrodynamic forces will further open the main poppet valve to allow full flow of high-pressure water to the nozzle. Releasing the trigger allows the pilot poppet spring to reseat the now balanced main poppet. Differential pressure then begins to take effect and seal the poppet as the downstream section drains to lower ambient pressure through the nozzle.



(a) As-building drawing (from Ref 2)

(b) Photograph

Figure 3. Cavitating waterjet pistol.

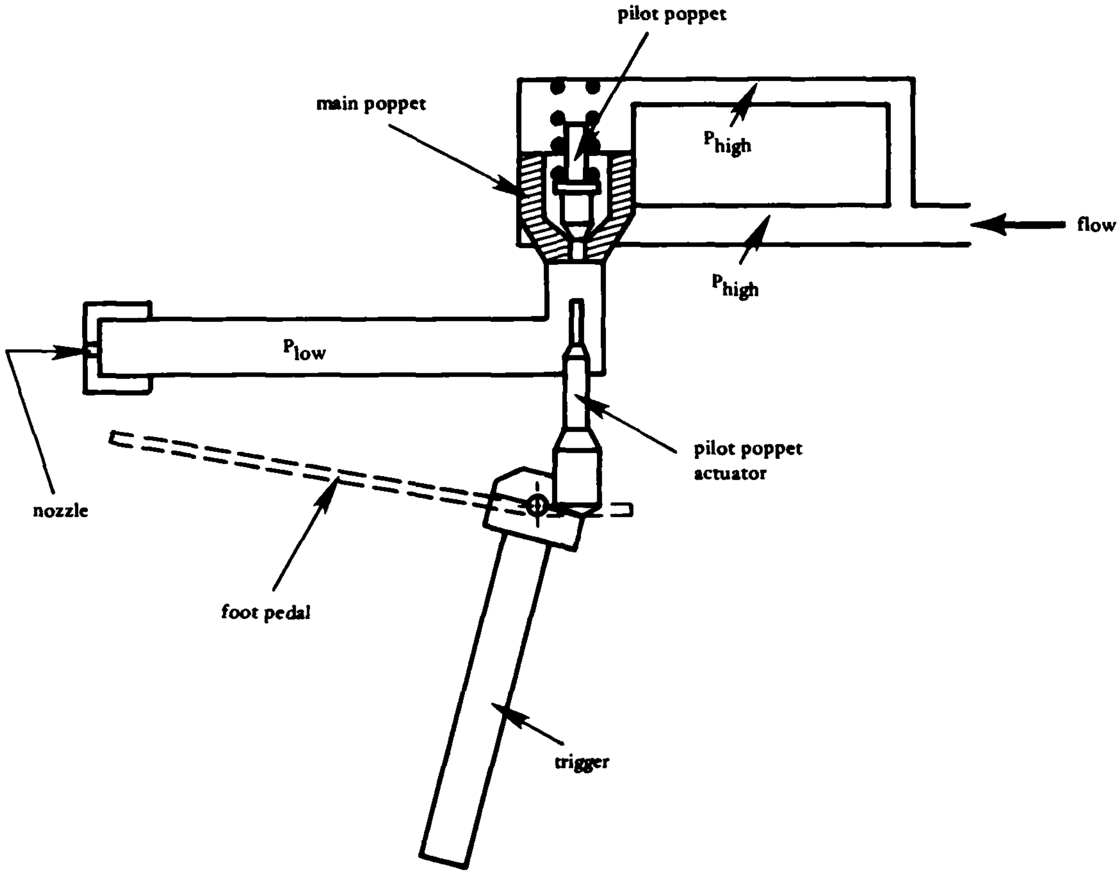


Figure 4. Pilot-operated trigger valve (from Ref 2).

Two types of nozzles were delivered for use with the tool: an aluminum-oxide (single-crystal sapphire) orifice nozzle available in sizes ranging from 0.003 to 0.125 inch in diameter, and a tungsten-carbide fan jet nozzle available in a wide range of angles and equivalent orifice diameters. Both of these nozzle options produce sufficient velocities at sharp-edged exits to result in excellent cavitation. The nozzles are mounted in similar holders that do not require the use of tools for easy changeout by a diver-operator wearing three-fingered gloves.

The as-built cleaning tool specifications are given in Table 3.

Power Unit. A modular-design power unit was developed by Flow Industries, Inc. to permit a variety of applications and to simplify fabrication, assembly, maintenance, and repair of the system. The power unit contains a drive module, a hydraulics module, and a high-pressure module. The modules are bolted together within a protective frame designed for forklift and crane handling.

Table 3. Specifications for the Waterjet Pistol Cleaning Tool

Item	Specification
Maximum Operating Pressure	12,000 psi
Maximum Flow Rate	3 gpm
Weight (in air)	5.04 lb
Operating Fluid	Freshwater
Trigger Pull at 10,000 psi	5.34 lb
Design Type	Direct-acting shutoff valve Pilot-operated, spring-actuated, normally closed
Safety Mechanism	Manual lock
Material	Stainless steel construction
Operating Depth	120 ft
Theoretical Jet Thrust	7.9 lb (0.031-in. straight nozzle)
Design Safety Factor	2:1 minimum
Nozzle	
Straight Jet	0.031-in. diameter
Fan Jet	0.029-in. equivalent diameter 8 to 10 deg flat fan angle

The drive module contains a Deutz air-cooled diesel engine, fuel tank, battery, and mufflers. The drive module also includes a direct-mounted, Denison variable-displacement, pressure-compensated piston pump and an auxiliary or precharge water pump. Engine controls and automatic safety shutdowns are located at the rear of the module where they may be easily accessed by the operator. The primary purpose of the drive module is to supply hydraulic oil pressure and inlet water to the pressure intensifier.

The hydraulics module contains the hydraulic oil reservoir, filters, relief valves, heat exchanger, pressure switches, and intensifier pressure controls. The hydraulic pump, which is mounted directly onto the engine, is part of the drive module. All of the components of the hydraulics module are mounted in a frame that bolts directly to the high-pressure module frame.

The high-pressure module contains the intensifier, an accumulator, and various hoses and fittings. The high-pressure module produces water as its output at a pressure four times that of the input pressure of the hydraulic oil intensifier. The protective framework housing the high-pressure module and the hydraulics module also serves as a mounting frame for the drive module.

A photograph of the power unit and a drawing of the hydraulic circuit are shown in Figures 5 and 6, respectively. The as-built power unit specifications are shown in Table 4.

Interconnecting Hardware. The interconnecting hardware includes three 50-foot, 5/16-inch-ID, high-pressure hose assemblies and the foot-actuated shutoff valve. The hoses are identical and can be attached in any order. Adapters have been added to all tool and power unit valves to standardize the fittings throughout the system. The foot valve and tool bodies and all of their internal parts are identical and interchangeable. The foot valve operates like the cleaning tool. To actuate the foot valve, the foot pedal is depressed to unseat the pilot poppet (Figure 4).

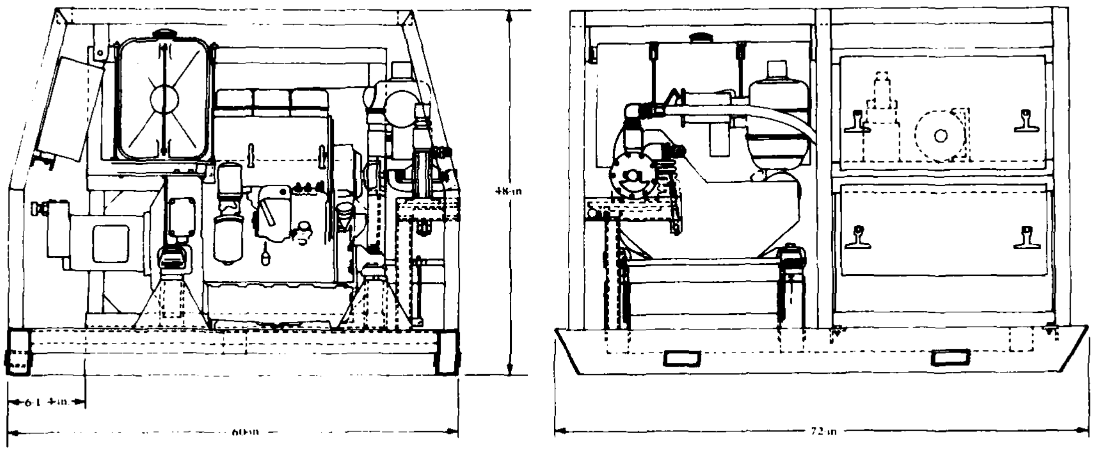
Acceptance Test And Delivery

Tests were carried out on all components both individually and assembled into a system. The power unit checkout and test consisted of setting and checking all emergency shutdowns and running the diesel engine and intensifier pump for 20 hours. This 20-hour checkout was performed at the normal 10,000-psi operating pressure. A preliminary cleaning tool and foot valve checkout was performed, followed by a 1-hour test at 10,000 psi to ensure proper function. Both the fan and straight jet nozzles were checked out for proper operation.

A 4-hour acceptance test was conducted at the contractor's facility. During this test, the cleaning tool and foot valve were cycled by several individuals to demonstrate proper performance. The cleaning tool was fitted with a tungsten-carbide fan jet nozzle for the test. It was then submerged in a tank of water and run for 4 hours at the 10,000-psi operating pressure. At the end of the 4-hour period, the cleaning tool was again cycled to ensure its proper functioning.

The tungsten-carbide fan jet nozzle used during the acceptance test suffered a certain amount of erosion or wear. This is because fan jet nozzles must at present be fabricated of metals such as tungsten-carbide rather than the harder diamond and sapphire used for circular-orifice or straight jet nozzles. Although diamond and sapphire nozzles are expected to last indefinitely at jet velocities corresponding to 10,000-psi water pressure, these materials are currently too expensive for use in fan jet nozzles. However, although susceptible to wear, tungsten-carbide fan jet nozzles generally provide very good service life at the required 10,000-psi operating pressure.

Fan nozzle configuration and method of manufacture strongly influence nozzle wear. Sharp corners and thin sections at the edges of some nozzles will erode slightly and then stabilize after a few hours of operation. This results in a slightly larger than optimum orifice and, consequently, a greater flow rate from the nozzle and greater thrust on the tool, provided the nozzle pressure remains constant.



(a) As-built drawing (from Ref 2)

(b) Photograph

Figure 5. Power unit.

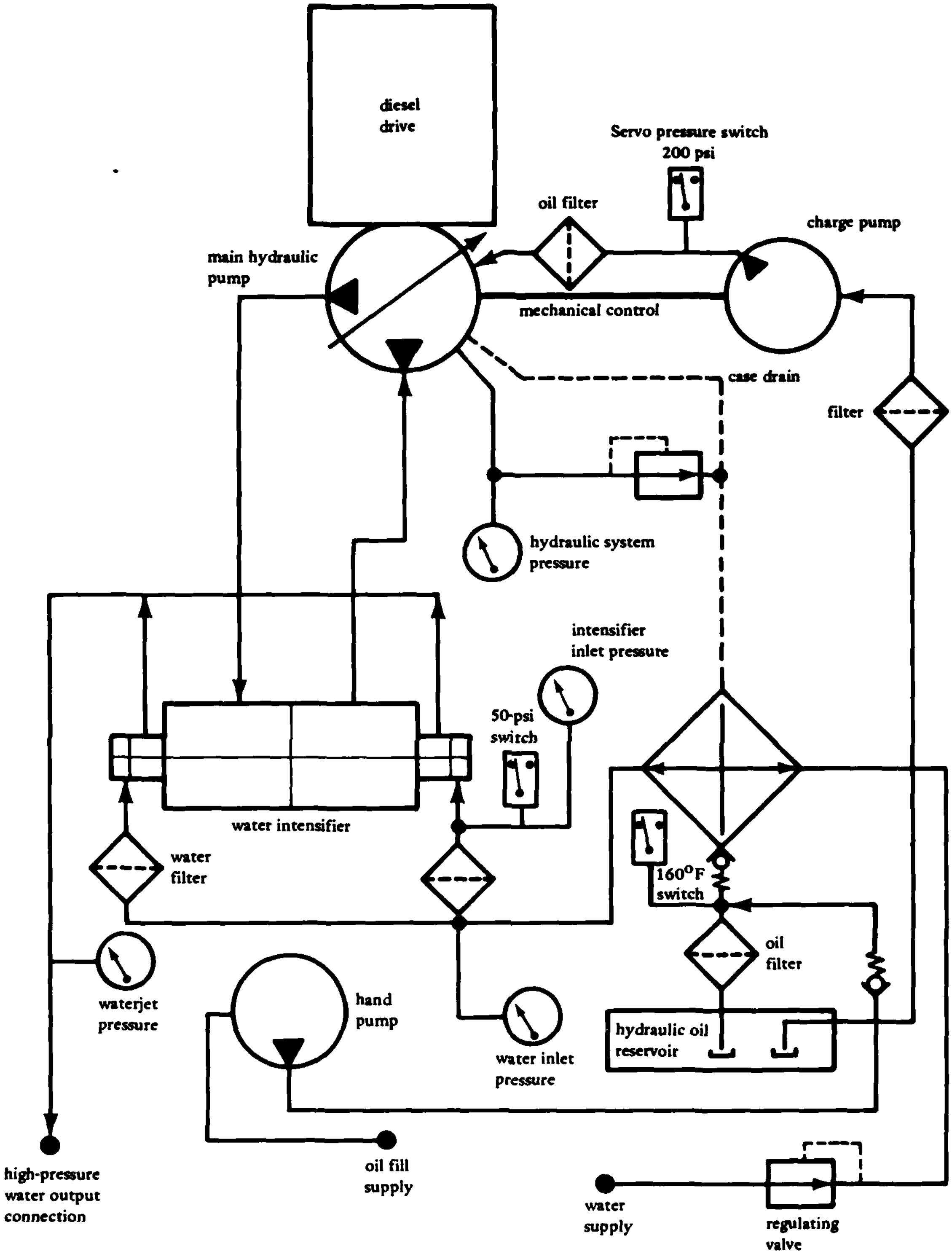


Figure 6. Power unit schematic diagram.

Table 4. Power Unit Specifications

Item	Specification
Flow Industries Model Number	
81 DM3 81 HPM12 82 HM	Diesel-drive module High-pressure module Hydraulics module
Dimensions	
Height Width Length Weight	4 ft 5 ft 6 ft 3,500 lb
Water Requirements	
Flow Booster Pump (optional) Filtration	5 gpm at 50 psi 5 gpm at 0 psi 10 μ
Water Output	
Flow Rate Pressure	0-3 gpm 0-12,000 psi
Engine - Deutz Diesel F3L912W	
Sea Level Rating Fuel Consumption Fuel Capacity	34 hp at 1,800 rpm 2 gph 24 gal
Engine Gages	Engine hour meter Engine oil pressure Tachometer Fuel level Cylinder head temperature Voltmeter Ammeter
Electrical System	12 V
Hydraulic Pump - Denison P6P (Variable-displacement, pressure-compensated piston pump)	
Displacement Maximum Continuous Pressure	6 in.^{3}/rev 3,000 psi
Hydraulic System (sealed, closed-loop)	
Oil Capacity Oil Type Filtration	15 gal Shell Tellus 68 or equivalent 10 μ
Hydraulic System Gages	Hydraulic system pressure Intensifier inlet pressure Inlet water pressure Outlet water pressure

After determining that the cleaning system had passed the acceptance test, the prototype high-pressure waterjet cleaning system was delivered to NCEL, along with a preliminary Operation and Maintenance Technical Manual, in September 1981.

PROTOTYPE TEST AND EVALUATION

During 1982, the prototype cleaning system was tested and evaluated in the laboratory and the field. The tests included nozzle erosion and reaction force tests, sound pressure level tests, damage versus distance tests, harbor field tests, and Underwater Construction Team Two (UCT-2) field tests. The nozzle erosion and reaction force tests were conducted simultaneously. The nozzle erosion tests determined the extent, if any, of nozzle wear with continued operation. The reaction force tests measured the reaction or backthrust of the waterjet pistol using various nozzle sizes. The sound pressure level tests measured the underwater sound levels generated by the waterjet pistol to determine if a hearing hazard exists for diver-operators. The damage versus distance tests measured the standoff distance required to prevent damage to various materials. The harbor field tests were conducted to evaluate overall system performance including cleaning capability, safety, and ease of use. Similarly, the UCT-2 field tests were conducted to evaluate system performance and as a preliminary step in obtaining Authorization for Navy Use (ANU).

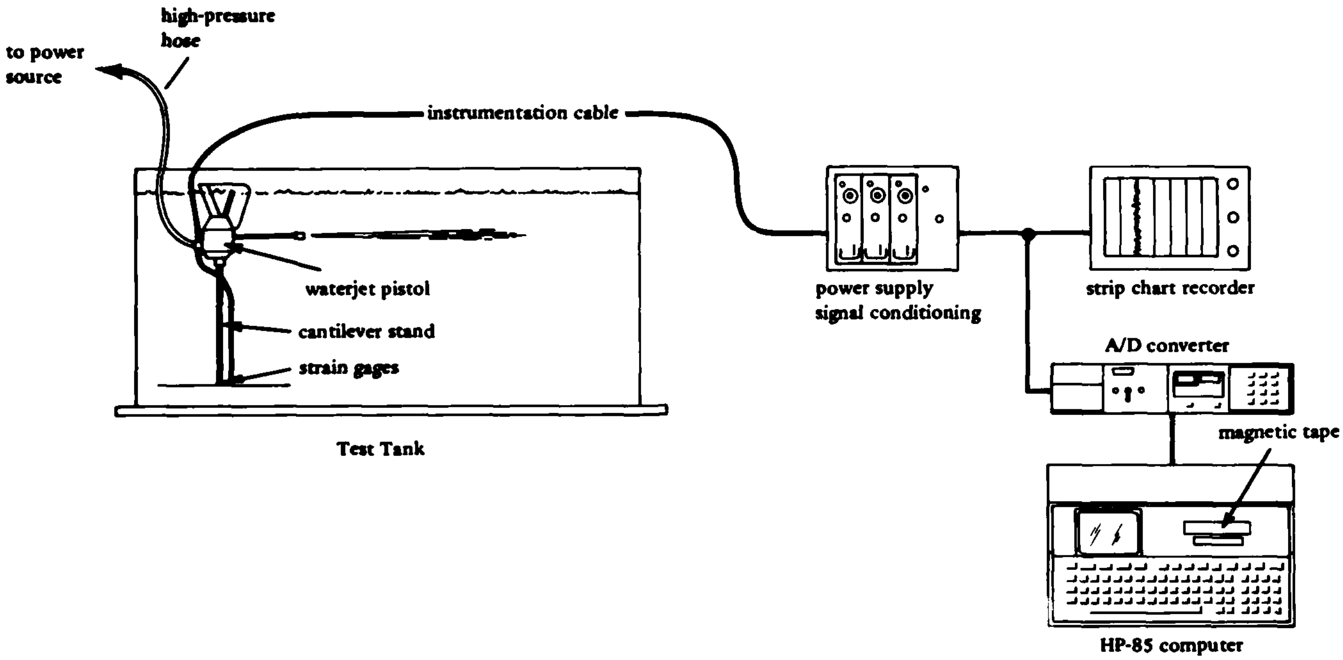
Nozzle Erosion And Reaction Force Tests

As a result of the nozzle wear that occurred during the contract 4-hour acceptance test, a series of tests was conducted to evaluate the rate of nozzle erosion. Four nozzles were used: a 0.031-inch straight jet, a 0.025-inch fan jet, a 0.031-inch fan jet, and a 0.039-inch fan jet.

During the tests, the cleaning tool was mounted in a stand that acted like a cantilever beam. A diagram and photographs of the test configuration are shown in Figure 7. A set of strain gages at the base of the cantilever measured the reaction force from the waterjet tool.

Nozzle size was measured with an optical comparator before and after each test run to determine if any wear had occurred. Also, the strain gage measurement of the reaction force was continuously output on a strip chart recorder, sampled and displayed on a digital voltmeter, and stored on magnetic tape using a Hewlett-Packard 85 microcomputer. By monitoring the reaction force, any significant changes in nozzle orifice size could be detected as a result of the increased mass flow through the nozzle.

Each nozzle was operated at 10,000 psi for more than 10 hours. No significant change in nozzle orifice size occurred during any of the tests. The data from the tests are summarized in Table 5. The average measured reaction force for each of the nozzles is as follows: 9.5 pounds for the 0.031-inch straight jet, 4.0 pounds for the 0.025-inch fan jet, 12.4 pounds for the 0.031-inch fan jet, and 16.1 pounds for the 0.039-inch fan jet.



(a) Schematic

(b) Photographs of cantilever

Figure 7. Nozzle erosion test set up.

Table 5. Reaction Force and Nozzle Erosion Test Data

Nozzle Time (hr)	0.025-in. Fan Jet			0.031-in. Fan Jet			0.039-in. Fan Jet			0.031-in. Straight Jet	
	Major Diameter (in.)	Minor Diameter (in.)	Reaction Force (lb)	Major Diameter (in.)	Minor Diameter (in.)	Reaction Force (lb)	Major Diameter (in.)	Minor Diameter (in.)	Reaction Force (lb)	Diameter (in.)	Reaction Force (lb)
0	0.02969	0.01011	3.9	0.05010	0.02003	11.9	0.05389	0.03024	15.1	0.03126	9.0
4	0.03079	0.01056	3.9	0.05115	0.02028	12.3	0.05406	0.03093	16.2	0.03126	9.4
11	0.03104	0.01135	4.2	0.05206	0.02030	13.0	0.05384	0.03121	16.3	0.03124	9.5
change	+0.00135	+0.00124	+0.3	+0.00196	+0.00027	+1.10	-0.00005	+0.00097	+1.2	-0.00002	+0.5

Based upon the results of the nozzle erosion and reaction force tests, it was concluded that no significant wear of the nozzle orifice should occur if the original nozzle is of standard quality and craftsmanship. Minor defects, such as sharp corners and thin edges, of fan jet nozzles can cause the orifice to wear during the initial hours of operation. To ensure reliability with respect to nozzle wear, it is recommended that fan jet nozzles be operated for a minimum of 4 hours before releasing for field use.

Sound Pressure Level Tests

Underwater noise measurements generated by the prototype high-pressure waterjet system were analyzed to determine if a hearing hazard existed for diver-operators. Initial tests were conducted at the Naval Coastal Systems Center (NCSC), Panama City, Fla., in December 1981. Measurements were made for SCUBA divers with and without the protection of a 1/4-inch wetsuit hood and also for MARK 12 divers. An overall average sound pressure level (OASPL) for the tool was determined based upon guidelines used by the Navy Experimental Diving Unit (NEDU) in the ANU process for diver tools. The OASPL was modified for underwater noise by correcting for reference level, A-weighting, and acoustic impedance mismatch as described in Reference 3. The OASPL was then compared with the Occupational Safety and Health Administration (OSHA) in-air standards to determine if a potential hearing hazard existed and, if so, to establish a time limit for the tool's underwater use. The OSHA criterion is based upon a maximum of 90 decibels for 8-hour exposure periods with a 5-decibels *trading relationship* (i.e., the allowable exposure time is halved for every 5-decibels increase in sound level).

Based upon the results of these tests, which are described in detail in Reference 4, it was recommended that a wetsuit hood be worn during tool use and no operating time limit be imposed. However, after reviewing the procedures for analysis of underwater sound pressure levels, the Chief of the Bureau of Medicine and Surgery (BUMED) in July 1982 determined that the guidelines in use at the Navy Experimental Diving Unit were too lenient and the underlying assumptions for the underwater correction factors may have been in error. In particular, the adjustments for acoustic impedance mismatch and A-weighting factor were questioned and the OSHA criteria were waived in lieu of the more stringent Department of Defense sound level damage risk criteria (Ref 5). While a comprehensive instruction on underwater noise limits is developed, BUMED has provided interim guidance for determining underwater noise levels (see Appendix A).

Damage Versus Distance Tests

In addition to the sound level measurement tests, damage versus distance tests were conducted at the Naval Coastal Systems Center to determine the standoff distance required to prevent damage to various materials. The three materials tested included 1/4-inch neoprene (wetsuit material) with a one-sided nylon cover, a bronze plate (propeller material), and a 3/16-inch plate of fiberglass. The two nozzles with greatest jet intensity were used: the 0.031-inch straight jet and the 0.039-inch fan jet.

For the damage-to-wetsuit-material tests, the 0.031-inch straight jet nozzle was initially positioned approximately 3 inches from the material and operated at 10,000 psi for 30 seconds. A 3/8-inch-long cut completely through the wetsuit material (neoprene and nylon) was measured. At a 4-1/4-inch standoff distance, a 3/8-inch-long cut occurred that penetrated only halfway through the wetsuit material after 30 seconds of operation. The nozzle was moved back to a 5-inch standoff distance and operated for 30 seconds, resulting in only slight abrasion of the wetsuit material. When the 0.031-inch nozzle was operated at a 6-inch standoff distance for 2-1/2 minutes, no damage to the wetsuit material was noted.

The 0.039-inch fan jet nozzle caused less severe damage than the 0.031-inch straight jet nozzle. At a 3-1/8-inch standoff distance, the tool was operated at 10,000 psi for 2-1/2 minutes with no visible damage to the wetsuit material occurring. The complete damage versus distance test data are shown in Table 6.

Harbor Field Tests

Field tests were conducted in Port Hueneme Harbor, Calif., to determine the cleaning capability, human factors and safety characteristics, and maintenance requirements of the NCEL high-pressure waterjet system. The cleaning system was evaluated based upon its ability to remove fouling and corrosion from the submerged portions of concrete and steel waterfront structures. Also, the human factors design of the waterjet pistol was evaluated.

Since most of the time required to completely clean underwater surfaces is spent removing the last remnants of stubborn shell growth and fouling, two cleaning times were recorded. Cleaning to remove moderate to heavy fouling consisting of weed growth, algae, rust, and loose barnacles or tubeworms was called "preliminary cleaning." Cleaning to remove all heavy fouling including stubborn shell growth and any protective coating was called "final cleaning." Based upon cleaning rates obtained in 1980 with various commercially available high-pressure waterjet devices (Ref 1), cleaning rates were established as criteria for evaluating the prototype system cleaning capability. The cleaning rate criteria are as follows:

Cleaning Rates (ft^2/min)

Surface	Preliminary	Final
Steel	2.50	1.20
Concrete	1.60	0.60

NOTE: The goal of the prototype cleaning tests was to achieve cleaning rates that exceeded the cleaning rate criteria.

The human factors evaluation included diver-operator comments on handling, maneuverability, hose stiffness, reaction force, trigger tension, hand or forearm fatigue, and noise level.

Table 6. Damage Versus Distance Test Results

Nozzle	Material	Standoff Distance (in.)	Operating Time (min)	Results
0.039-in. fan jet	1/2-in. neoprene (wetsuit material) one-sided nylon lining	3-1/8	0.5	No damage
		3-1/8	2.5	No damage
		2	0.5	1/2-in.-long cut partially into neoprene, but nylon undamaged
		1-3/8	0.5	1-in.-long cut through neoprene, but nylon undamaged
		1	0.5	1-in.-long cut through neoprene and nylon
	Fiberglass plate (3/16 in. thick)	1-3/8	1.0	No damage
		3/4	1.0	5/8- by 1/8- by 1/16-in. deep groove in 3/4- by 1/2-in. abraded area
		3/8	1.0	3/4- by 1/8- by 1/8-in. deep groove in 1- by 1-in. abraded area
	Bronze plate (propeller sample)	1	5.0	No damage
		3/8	5.0	No damage; 1/2- by 1/8-in. polished area

continued

Table 6. Continued

Nozzle	Material	Standoff Distance (in.)	Operating Time (min)	Results
0.031-in. straight jet	1/4-in. neoprene (wetsuit material)	6	2.5	No damage
		5-1/8	0.5	No damage; mild abrasion
		5-1/8	2.5	1/4- by 1/4-in. cut halfway into neoprene
	1/4-in. neoprene (wetsuit material)	4-1/4	0.5	3/8- by 1/4-in. cut approximately halfway into neoprene; nylon undamaged
		3-1/8	1.0	3/8- by 1/4-in. cut through neoprene and nylon
	Fiberglass plate (3/16 in. thick)	3-1/8	1.0	No damage
		1-3/8	1.0	3/8- by 1/8- by 1/16-in. deep groove
	Bronze plate (propeller sample)	1	5.0	No damage
		1/2	5.0	1/8-in by 1/16-in. area of light abrasion

After a topside safety and operational briefing, two divers were deployed with the cleaning tool and underwater video equipment. The initial surface condition of the steel or concrete piling was documented on video. A portion of the piling was then measured and roped off for cleaning. After the cleaning was completed, the final surface condition was documented and the operator's comments were recorded. Seven different Navy divers operated the cleaning system during the underwater tests (Figure 8). The four available nozzles were evaluated at three different operating pressures: 8,000, 10,000, and 12,000 psi.

As expected, the major factors affecting the cleaning rate included diver experience with the tool, operating technique, and type of fouling. Increasing the flow rate (by using a larger nozzle) or the pressure did not result in a corresponding increase in cleaning rate because at higher flows and pressures the reaction force of the tool is greater and the operation of the tool becomes more difficult and fatiguing. A tradeoff occurs between ease of handling (reaction force) and hydraulic power (pressure and flow). The results of the cleaning tests are given in Table 7 and summarized in Table 8.

On concrete surfaces, where marine fouling tends to be more tenacious and adherent, the average preliminary and final cleaning rates were less than the established criteria. The prototype waterblaster quickly removed all loose material, but more time was required to remove the stubborn shell growth found on most underwater concrete structures. This was as expected, since during the original commercial cleaning systems evaluation it was determined that the optimum device for thoroughly cleaning concrete structures was not a waterblaster but a device called the "Whirl Away." The Whirl Away, available from Robert C. Collins Co., is a rotary abrading attachment that fits a standard hydraulic grinder or drill (Figure 1). This device achieved an average final cleaning rate of 0.68 ft^2/min on concrete surfaces during the commercial cleaning systems evaluation in 1979. Preliminary cleaning rates for the Whirl Away were not recorded because the rotating blades quickly and effectively cleaned concrete piling to the base material.

The average preliminary cleaning rates on steel piling were all faster than the 2.50 ft^2/min criterion. The maximum preliminary cleaning rate, achieved with the 0.025-inch fan jet nozzle, was 3.66 ft^2/min. The average final cleaning rates on steel piling were less than the 1.20 ft^2/min criterion. The maximum final cleaning rate, achieved with the 0.031-inch fan jet nozzle, was 1.04 ft^2/min, which is 13% less than the established criterion. Since the final cleaning rates on steel structures were lower than desired, several modifications were planned for the prototype cleaning system. The modifications that were made in late 1982 and early 1983 are discussed in detail in the PROTOTYPE MODIFICATIONS section.

UCT-2 Field Tests

In March 1982, the Officer in Charge of UCT-2 requested that the NCEL prototype cleaning system be made available for operational tests during the summer of 1982. UCT-2 had been tasked to repair a bridge in Subic Bay, RP. The bridge repair required that the steel piles be thoroughly cleaned.

Figure 8. NCEL Port Hueneme Harbor field test.

Table 7. Spring 1982 Cleaning Test Results

Test	Nozzle	Pressure (psi)	Operator	Preliminary Rate (ft^2/min)	Final Rate (ft^2/min)
			Steel H-Piling		
1	0.025-in. fan jet	8,000	Diver 1	3.47	0.45
2		10,000	Diver 1	1.21	0.72
3		12,000	Diver 2	6.31	0.51
4	0.031-in. fan jet	8,000	Diver 1	1.95	0.89
5		10,000	Diver 1	1.75	0.95
6		10,000	Diver 1	3.73	0.98
7		12,000	Diver 1	3.29	1.35
8	0.039-in. fan jet	8,000	Diver 3	1.11	0.74
9		8,000	Diver 3	2.55	0.73
10		10,000	Diver 3	2.85	1.13
11		12,000	Diver 4	3.73	0.49
12	0.031-in. straight jet	8,000	Diver 4	3.29	0.57
13		10,000	Diver 1	1.91	0.70
14		12,000	Diver 1	2.86	1.20
			Concrete Piling		
15	0.031-in. fan jet	8,000	Diver 5	0.77	0.36
16		10,000	Diver 5	1.64	0.39
17		12,000	Diver 5	2.31	0.54
18	0.039-in. fan jet	8,000	Diver 6	0.89	0.42
19		10,000	Diver 6	1.95	0.30
20		12,000	Diver 7	0.76	0.27
21	0.031-in. straight jet	10,000	Diver 8	0.79	0.31
22		12,000	Diver 8	0.95	0.36

Table 8. Spring 1982 Cleaning Test Results Summary

Nozzle	Cleaning Rates (ft^2/min) on--			
	Steel		Concrete	
	Preliminary	Final	Preliminary	Final
0.025-in. fan jet	3.66	0.56	---	---
0.031-in. fan jet	2.68	1.04	1.57	0.43
0.039-in. fan jet	2.56	0.77	1.20	0.33
0.031-in. straight jet	2.69	0.83	0.87	0.34

NCEL delivered the prototype cleaning system to UCT-2 and provided a technical expert to instruct UCT-2 personnel in the proper operation and maintenance of the cleaning system. The Navy Experimental Diving Unit (NEDU) developed a test plan that contained a Data and Critique Sheet and an Individual's Questionnaire to be filled out by UCT-2 personnel onsite.

When the cleaning system arrived in Subic Bay, RP, the repair work on the steel H-piles had been completed by UCT-2 ahead of schedule. The NCEL technical representative developed a test scenario with UCT-2 that entailed cleaning concrete piling in the Subic Bay vicinity. Although it was already known that the NCEL cleaning system was less suited for cleaning concrete piling, it was felt that the evaluation would still provide valuable data on operational and handling characteristics.

In general, the diver comments obtained from the field evaluation confirmed the results from the Port Hueneme Harbor field tests. The diver-operators felt that the Whirl Away hydraulic tool was superior to the prototype waterblaster in cleaning capability. However, one diver commented that the Whirl Away was suited only for flat surfaces and could not clean in corners or other limited access areas. When comparing the NCEL prototype to a commercial high-pressure waterblaster that they had used earlier in their task, the consensus was that the NCEL prototype was the better tool. The operators felt that the waterjet pistol was preferable to the larger commercial retrojet gun because of its maneuverability, light weight, and easier trigger pull. Also, the divers commented on the ease of handling the high-pressure supply hose of the prototype in comparison to other hoses they had experience using.

Suggestions for improving the ease of operation of the prototype system included developing a shoulder stock or vertical grip to help support the tool while operating it underwater and improving the trigger safety locking mechanism. A summary of the questionnaires and critique sheets is shown in Figure 9. The completed questionnaires and critique sheets are included in Appendix B.

PROTOTYPE MODIFICATIONS

The following is a list of comments or recommendations that were compiled during the testing at NCSC, Panama City, Fla.; at Port Hueneme Harbor, Calif.; and at Subic Bay, RP.

1. The clearance under the trigger lever is too small and could pinch the diver's glove and prevent the valve from closing. Since the hand force required to actuate the valve is so small, it could be resolved by shortening the lever.

2. The trigger guard should be stronger. It is too pliable and could bend if hit against something. This could jam the trigger lever in the ON position if the guard is deformed during operation.

INDIVIDUAL'S QUESTIONNAIRE FOR JET-PAC HIGH PRESSURE WATERJET CLEANING SYSTEM

This questionnaire is to be completed once by all personnel associated with the on-site testing of the waterjet system after about one week of use. (Circle answers where appropriate)

1. Name (Last, First, Middle) ______

2. Rate/Rank: ______

3. Duty Address: UCT-2 PORT HUENEME, CALIFORNIA

4. Previous experience with other high pressure waterjet cleaning tools? 1. YES 2. NO

5. Previous experience with other underwater cleaning tools? 1. YES 2. NO

6. If answer to 4 or 5 was YES, specify which tools and how does this waterjet compare with them: PARTEK WATERBLASTER - CLEANING WAS ABOUT THE SAME. THE NCEL WATERJET IS ALOT LIGHTER, HAS AN EASIER TRIGGER PULL, AND ITS WATER SUPPLY HOSE IS EASIER TO MANIPULATE IN WATER. THE WHIRL AWAY CLEANS CONCRETE BETTER THAN THE NCEL WATERJET BUT IS BY FAR ALOT MORE CUMBERSOME. ALSO, THE WHIRL AWAY IS ONLY EFFECTIVE ON SMOOTH FLAT SURFACES.

7. Location: ______

8. Type of structure cleaned: 1. Concrete 2. Steel H Pile 3. Sheet Pile 4. Other (explain)

______

8. Type of fouling on the structures? (Circle as many as appropriate):

1. Barnacles 2. Tube worm 3. Mussels 4. Kelp 5. Rust 6. Scale

7. Slime 8. Coral 9. Other ______

9. Amount of fouling:

1. Light (1") 2. Moderate (2") 3. Heavy (3" or more)

ANNEX C

10. How did the waterjet tool clean?

1. Excellent - Cleaned to structure base surface quickly

2. Good - Removed fouling agent(s) generally to base surface but required time

3. Poor - Did not do the job effectively or efficiently

11. Did you feel any effects from the underwater noise? 1. YES 2. NO
If YES, please explain: ______

12. Did you feel any hand or arm fatigue? 1. YES 2. NO

13. How long did you operate the tool each dive? 25 min

14. Were any operating, safety or handling problems encountered or noted regarding the:

High pressure hose	1. YES	2. NO
Waterjet pistol	1. YES	2. NO
Power source	1. YES	2. NO
Foot valve	1. YES	2. NO

15. If you answered YES to any of the above, please explain: ______

16. Do you have any recommendations to improve the cleaning ability, safety, or handling of the waterjet tool? 1. YES 2. NO

If YES, please explain: ______

A SHOULDER STOCK WOULD BE HELPFUL

Figure 9. UCT-2 data sheet summary.

3. The trigger locking mechanism can jam in either the ON or OFF position. This needs to be reworked.

4. The trigger locking mechanism should be redesigned so that it is double-sided for right- and left-handed operation and also spring loaded so whenever the trigger lever is released the lock automatically engages.

5. A quick disconnect shoulder stock would improve the ease of use by helping the diver support the reaction force.

6. The foot valve needs a plate in the end of it to prevent the operator's foot from getting caught inside.

7. Swivels at each high-pressure hose connection would prevent problems with kinks in the line and improve handling.

8. A blow-out disk on the waterjet tool would increase safety by preventing overpressurization if the power source malfunctions.

9. A valve should be installed on the power source to relieve the pressure in the hoses when the trigger valve is OFF.

10. Guides or tubing across the bottom of the power source skid would improve transportation with a forklift.

11. The power source should be modified to power hydraulic tools.

12. The power source should be modified to operate on seawater rather than just freshwater.

Based upon the results of all the tests conducted in 1981 and 1982, several modifications were designed for the prototype cleaning system. All 12 of the above recommendations for modifications were incorporated in late 1982 and early 1983. The trigger lever was shortened by 1 inch and the trigger guard was replaced with a stronger material. Reversing the bolts on the inside of the foot valve resolved the problem of snagging the operator's foot. A temporary shoulder stock was built to test the idea of providing a support to help the diver brace against the reaction force.

A new trigger locking mechanism was designed that allowed right- or left-handed operation. To actuate the trigger valve in the new design, the operator must initially push the safety catch forward. The mechanism automatically locks in the OFF position whenever the trigger lever is released. The automatic safety catch was designed so a diver could release it and operate the tool in a one-handed operation while wearing wetsuit gloves.

High-pressure quick disconnects for the hose connections and a high-pressure swivel for the hose connection to the waterjet pistol were installed. Also, based on Reference 6, new high-pressure supply hose was purchased. The hose, Synflex 3V10 with Surlin jacketing, was rated the best among nine different types of hoses based upon flexibility, abrasion resistance, corrosion resistance, tension effects under pressure, burst pressure and failure modes, and hose pulsation effects (Ref 6).

A modification to the valve body was designed so that a blow-out or rupture disk could be installed. The rupture disk is located adjacent to the pilot-operated trigger valve on the supply hose side. Since the power source is capable of producing up to 12,000 psi, a 15,000-psi rupture disk was used as recommended by the disk manufacturer, Continental Disk Manufacturing Co., Kansas City, Mo.

An ON/OFF valve was installed on the power source so that pressure could be bled from the system without having to actuate the waterjet pistol trigger valve. The bleed valve is located on the front of the unit near the pressure gages.

Tubing was welded onto the power source skid between the existing forklift slots. This simplifies moving the power unit and also acts as a guide to prevent the forklift from accidentally puncturing the base of the system. The power unit was also modified to supply oil hydraulic tools. Since the system uses a pressure intensifier and variable-displacement hydraulic pump, the modification was easily accomplished by tapping into the high-pressure side of the Denison hydraulic pump. The installed auxiliary hydraulic circuit provides both open and closed loop capabilities. The auxiliary hydraulic circuit is shown in Figure 10.

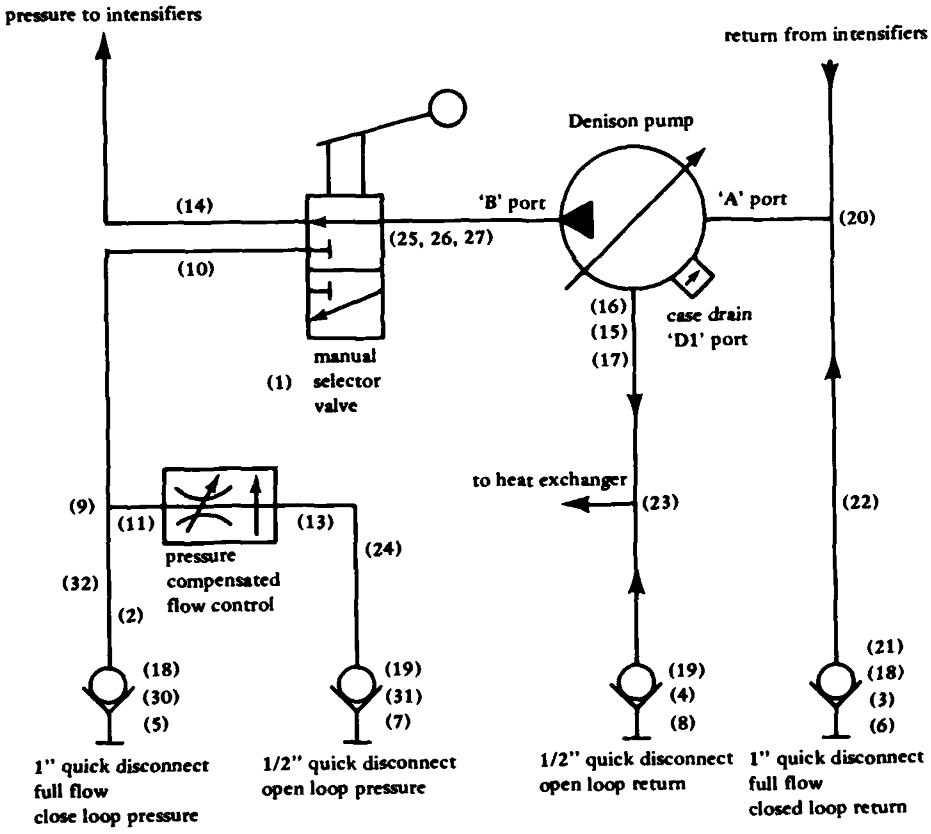
For applications where 250 psi cannot be tolerated on the return or tank side of the hydraulic circuit, a maximum of 7 gpm is available for auxiliary use. The oil pressure can be varied from 0 to 3,000 psi. In this open loop circuit, high pressure oil is taken from port "B" of the Denison hydraulic pump and low-pressure oil is returned to the system ahead of the heat exchanger.

For applications where 250 psi in the tank or return line is not a problem, the full 20-gpm pump flow can be used. Here again, the oil pressure can be varied from 0 to 3,000 psi. In this closed loop circuit, high pressure oil is taken from port "B" of the Denison hydraulic pump and supercharge oil (return) is put back into port "A."

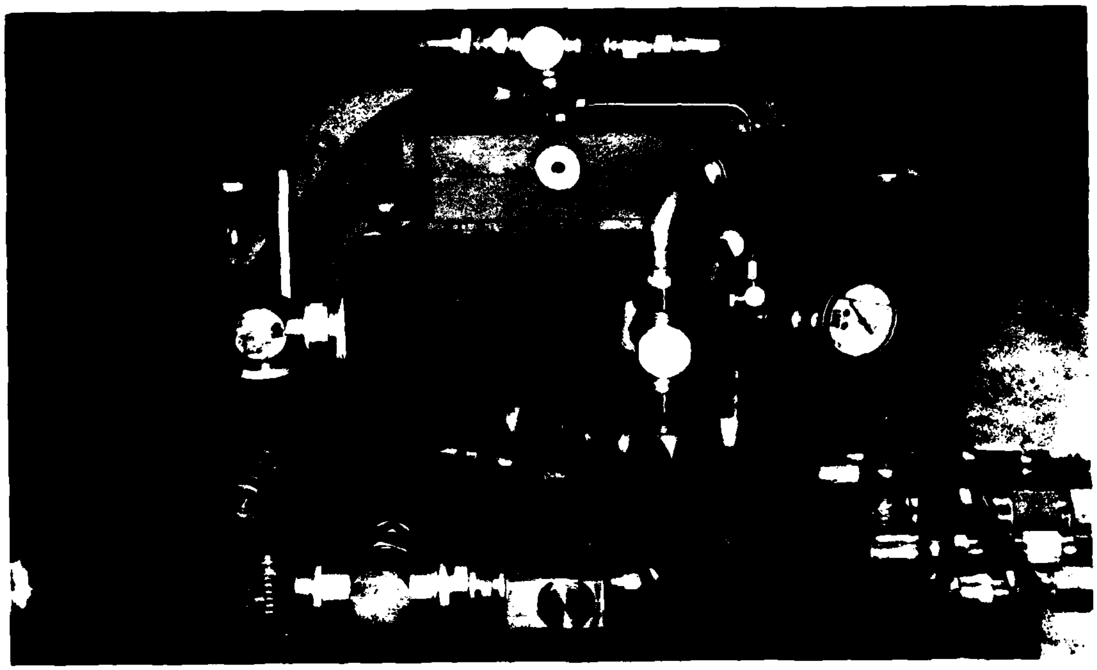
The operator can select the high-pressure waterjet system or the auxiliary hydraulics system by setting the Manual Selector Valve Lever located under the front control panel and near the hydraulic pump.

The prototype cleaning system was also modified to operate on seawater as well as freshwater. This modification is particularly helpful at remote locations or wherever a freshwater supply is not readily available. The only hardware modifications to the system involved replacing the heat exchanger and some parts in the pressure intensifier to protect against corrosion. The intensifier parts included seals, check valves, inlet casings, and piston shafts. In addition to the intensifier modifications, a sump pump was required to supply seawater to the inlet precharge pump.

At the recommendation of the manufacturer, Flow Industries, Inc., auxiliary hydraulic oil cooling was added to the power unit. The modification entails bleeding approximately 1 gpm of hydraulic oil from the supercharge side of the hydraulic circuit. This hydraulic oil is then routed through the heat exchanger to the hydraulic oil reservoir.



(a) Schematic



(b) Photograph

Figure 10. Auxiliary hydraulic retrofit.

These modifications were successfully completed by the end of February 1983. The modified prototype cleaning system was tested in the laboratory. A new series of field tests was scheduled to obtain updated performance data on the modified system. The modified prototype cleaning system is shown in Figures 11, 12, and 13.

MODIFIED PROTOTYPE TEST AND EVALUATION

In April 1983 the modified prototype cleaning system was evaluated during a series of field tests in Port Hueneme Harbor and near Anacapa Island, Calif. The tests were conducted to evaluate:

- The cleaning capability and operational aspects of the modified prototype.
- The modification to operate underwater hydraulic diver tools.
- The modification to operate with seawater instead of freshwater.
- Sound pressure levels produced by the four available nozzles.

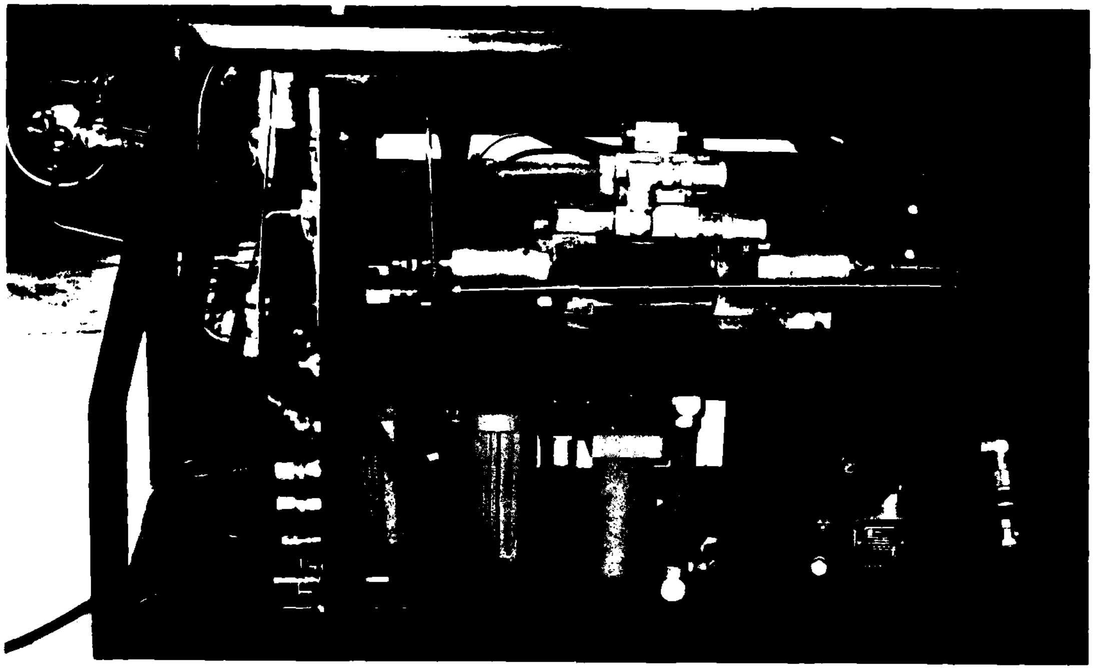
Cleaning Capability And Operational Tests

The cleaning capability and operational evaluation tests were conducted on steel and concrete piling in Port Hueneme Harbor. These tests were conducted using freshwater pressurized to 10,000 psi. Four nozzles were used:

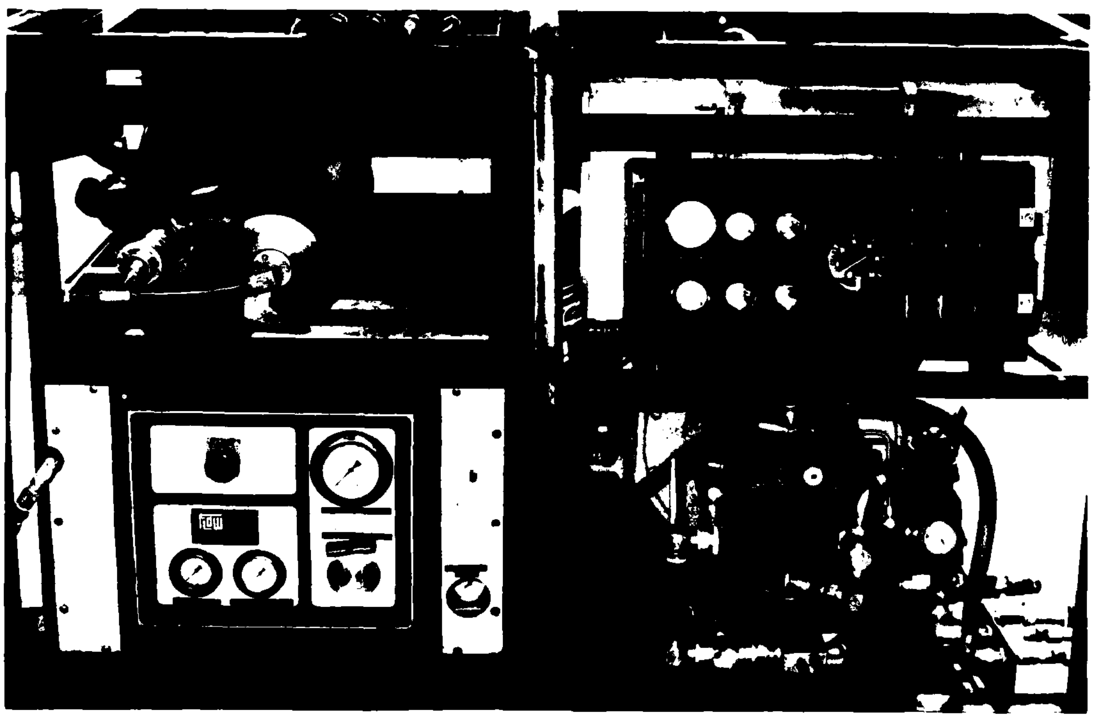
- the 0.031-inch straight jet
- the 0.025-inch fan jet
- the 0.031-inch fan jet
- the 0.039-inch fan jet

The evaluation of cleaning capability was based upon the waterblaster's ability to remove marine fouling and corrosion from submerged concrete and steel piling. Two cleaning rates were recorded as before: a preliminary rate, which included the removal of loose moderate to heavy fouling; and a final rate, which included the removal of all heavy fouling. The same cleaning rate criteria from the previous field testing were used as a basis for evaluation. The criteria included preliminary cleaning rates of 2.5 ft^2/min on steel and 1.6 ft^2/min on concrete, and final cleaning rates of 1.2 ft^2/min on steel and 0.6 ft^2/min on concrete.

The operational evaluation was based upon diver feedback recorded on individual questionnaire forms and from debriefings after underwater use. Also, feedback from topside personnel, including the power source operator, foot valve operator, and diving supervisor, was recorded.



(a) Closeup of intensifier circuit



(b) Front view

Figure 11. Modified prototype power source.

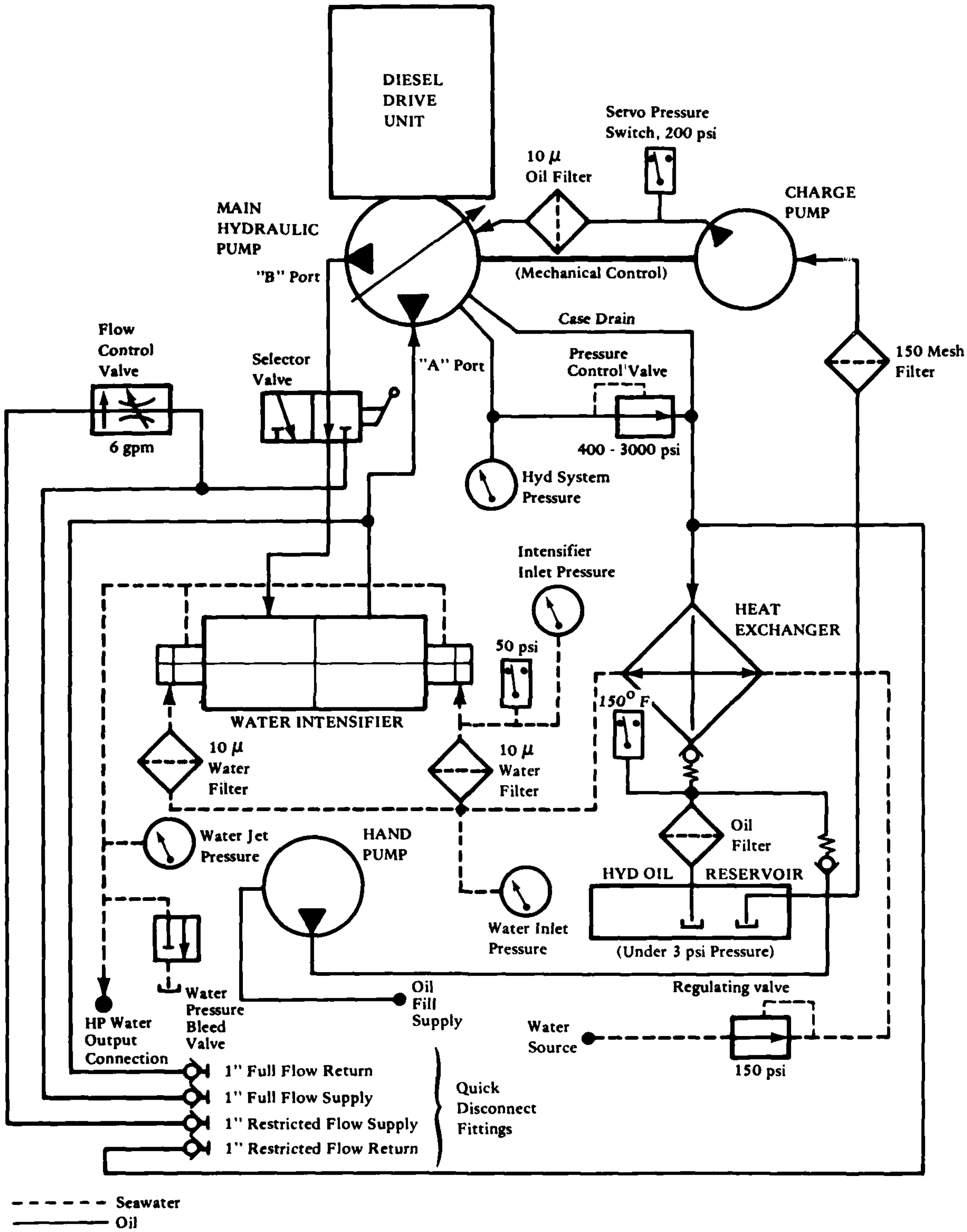


Figure 12. Simplified schematic diagram of modified prototype power source (from Ref 8).

(a) Hose over the shoulder

(b) Hose under the arm

Figure 13. Modified prototype waterjet pistol.

The procedure for the cleaning and operational evaluation tests was the same as in the previous cleaning system evaluation tests. After a topside safety and operational briefing, two divers were deployed with the cleaning tool and underwater video equipment. The initial surface condition of the steel or concrete piling was documented on video. A portion of the piling was then measured and roped off for cleaning. After the cleaning was completed, the final surface condition was documented and the operator's comments were recorded. Five different Navy divers operated the cleaning system during the cleaning capability and operational evaluation.

The first set of cleaning capability tests was conducted on steel piling. After the first few tests, it was determined that a preliminary cleaning was unnecessary since the modified waterblaster produced a "final-cleaning" quality on the first pass over the steel surface. Therefore, throughout the remainder of the tests only one cleaning rate was recorded. This rate was equivalent to a final cleaning in the previous tests for all of the steel piling cases.

The results of the steel cleaning capability tests are shown in Figure 14 and Table 9. The 0.031-inch straight jet nozzle achieved the highest cleaning rate of 8.63 ft^2/min on a flat surface that was easily accessible. All of the average cleaning rates were greater than the evaluation criteria of 2.5 ft^2/min, except for the 0.025-inch fan jet nozzle, which had a 2.41-ft^2/min average rate. The major factor affecting the cleaning rate was again found to be the experience and operating technique of the diver-operator. The nozzle type, the fouling amount, and the piling configuration were also found to affect the cleaning rate to a lesser extent.

The results of the concrete waterblaster tests are shown in Figure 15 and Table 9. As expected, the high-pressure waterjet was not as effective on concrete structures as on steel structures. Only one cleaning rate was recorded, however, because the waterblaster could not achieve a final-cleaning quality in a reasonable amount of time. The concrete piling in Port Hueneme Harbor tended to have a large amount of stubborn shell growth, such as barnacles and tubeworms, embedded in the surface. The divers were instructed to clean as much of the heavy fouling as possible without spending excessive amounts of time in detailed cleaning. The cleaning rates for concrete were then based upon a final surface condition with approximately 80% of the fouling removed. This cleaning rate falls somewhere between the earlier definition of preliminary and final cleaning.

The 0.031-inch straight jet nozzle was the only nozzle to achieve an average cleaning rate on concrete greater than the final cleaning performance criterion of 0.60 ft^2/min. The other three nozzles did not meet the established performance criteria. It is recommended that the 0.031-inch straight jet nozzle be used to clean concrete underwater structures in remote or limited access areas or if only a cursory cleaning to remove light to moderate fouling is required. If all the fouling must be removed to the base material and accessibility is not a problem, it is recommended that a hydraulic abrading tool, such as the Whirl Away by R.C. Collins Co., be used.

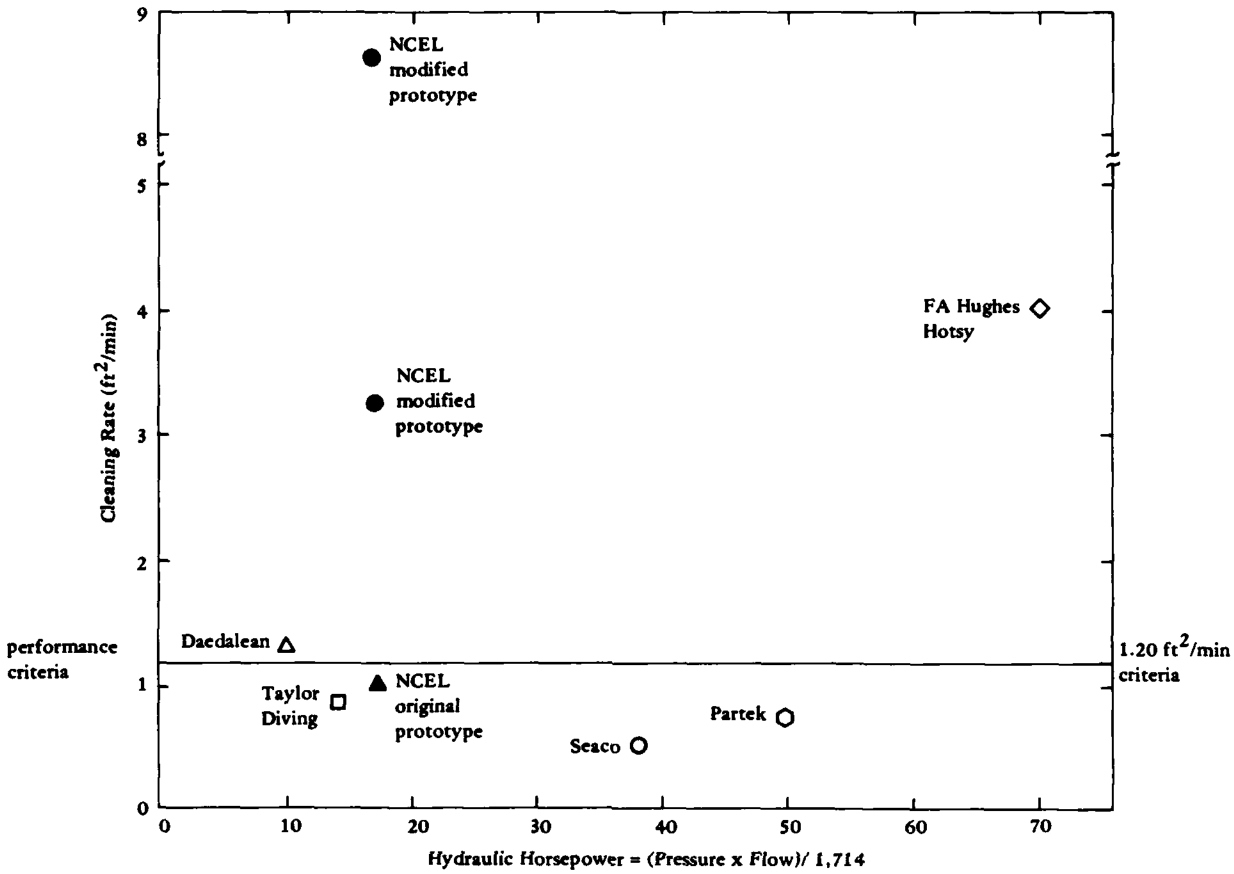


Figure 14. Steel cleaning capability tests.

Diver feedback during the high-pressure cleaning tests was favorable. Some of the divers who operated the tool had used the original unmodified prototype the year before and felt that the system had greatly improved in safety, ease of handling, and cleaning capability. The divers did recommend that a sturdier shoulder stock be developed since the temporary one used during the tests definitely improved the ease of use. Some of the diver-operators had used other commercially available waterblasters and felt that the prototype was operationally superior. The responses from the completed diver questionnaires can be found in Appendix B.

Auxiliary Hydraulic Tests

To evaluate the performance of the auxiliary hydraulics modification, the Whirl Away rotary abrading tool was used to clean concrete piling in Port Hueneme Harbor. The Whirl Away was attached to a Stanley hydraulic grinder. The same cleaning rate criteria and test procedures were used as during the prototype waterblaster tests. Only a final cleaning rate was recorded, since the Whirl Away quickly and effectively cleaned the concrete piling to the base material. All of the cleaning rates from the nine tests that were conducted greatly exceeded the final cleaning rate criterion of 0.60 ft^2/min. An average final cleaning rate of 6.52 ft^2/min was achieved, with a high of 11.37 ft^2/min and a low of 4.03 ft^2/min. The results are shown in Figure 16 and Table 9.

Table 9. Spring 1983 Cleaning Test Results

Test	Nozzle/Tool	Pressure (psi)	Operator	Cleaning Rate (ft^2/min)
		Steel H-Piling		
1	0.025-in. fan jet	10,000	Diver 1	2.41
2	0.031-in. fan jet	10,000	Diver 1	2.78
3				2.48
4				2.48
5				5.34
6	0.039-in. fan jet	10,000	Diver 1	6.10
7			Diver 2	1.05
8			Diver 2	1.11
9			Diver 2	2.73
10			Diver 3	1.03
11			Diver 3	1.60
12	0.031-in. straight jet	10,000	Diver 1	8.63
13				8.17
		Concrete Piling		
1	0.031-in. fan jet	12,000	Diver 4	0.25
2		10,000	Diver 4	0.19
3	0.039-in. fan jet	10,000	Diver 2	0.15
4	0.031-in. straight jet	10,000	Diver 2	2.36
5				0.14
6				0.24
7				0.29
1	Whirl Away		Diver 5	4.69
2				4.03
3				4.98
4				7.96
5				4.98
6			Diver 6	5.32
7				10.00
8				5.32
9				11.37

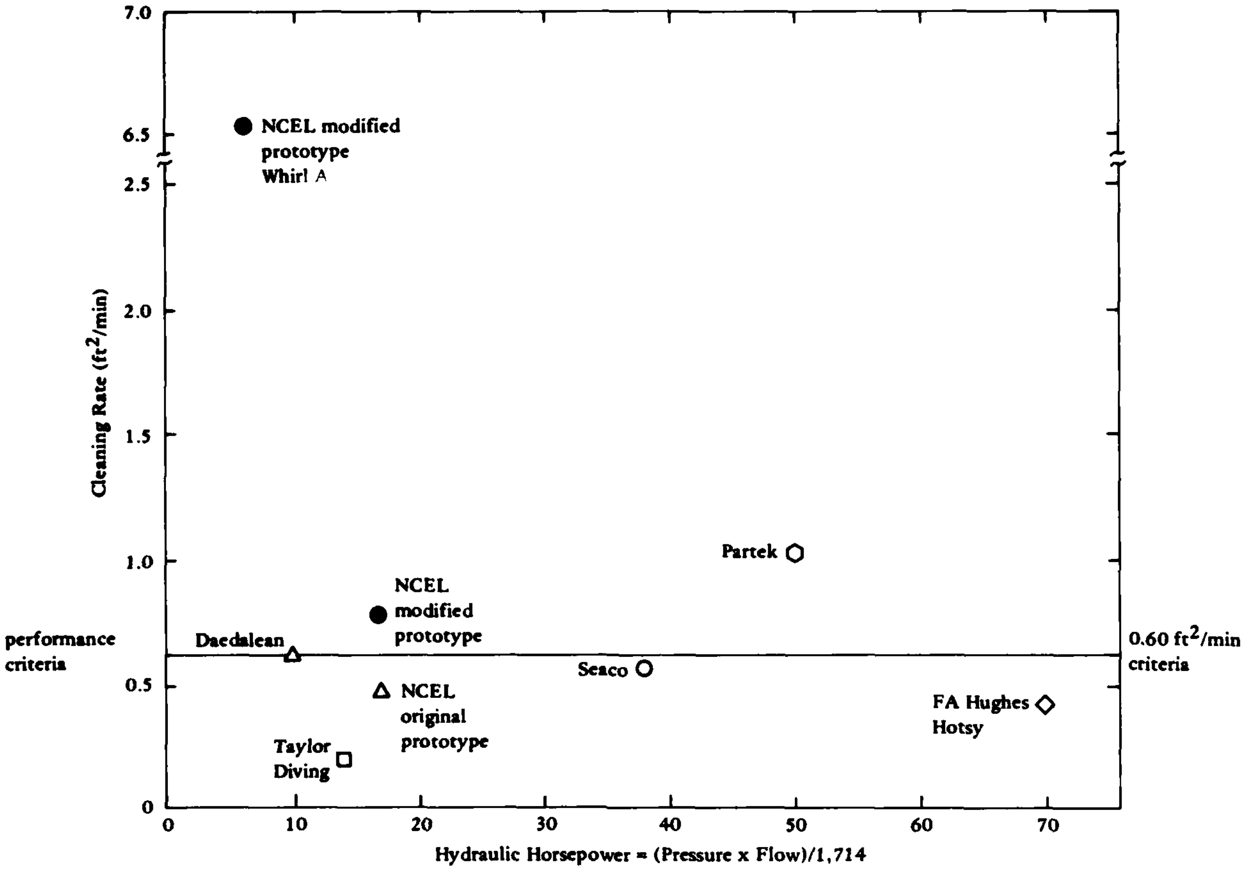


Figure 15. Concrete cleaning capability tests.

Operationally, the divers felt that the hydraulic tool was heavy; therefore, a float was attached to the hydraulic supply line to improve the ease of use. Also, one diver suggested that a shroud or shield should be added to the Whirl Away to protect the diver from the exposed rotating blades.

The Whirl Away is not as effective as the prototype waterblaster on steel underwater structures because on steel surfaces the waterblaster tends to get under the fouling and lift off large pieces of growth and corrosion. On concrete surfaces, if the fouling consists of barnacles, tubeworms, or other calcareous growth, the waterblaster is less effective than the Whirl Away, which breaks up the shell growth and leaves a smooth and clean surface. Table 10 is a summary of the waterblaster and Whirl Away cleaning tests.

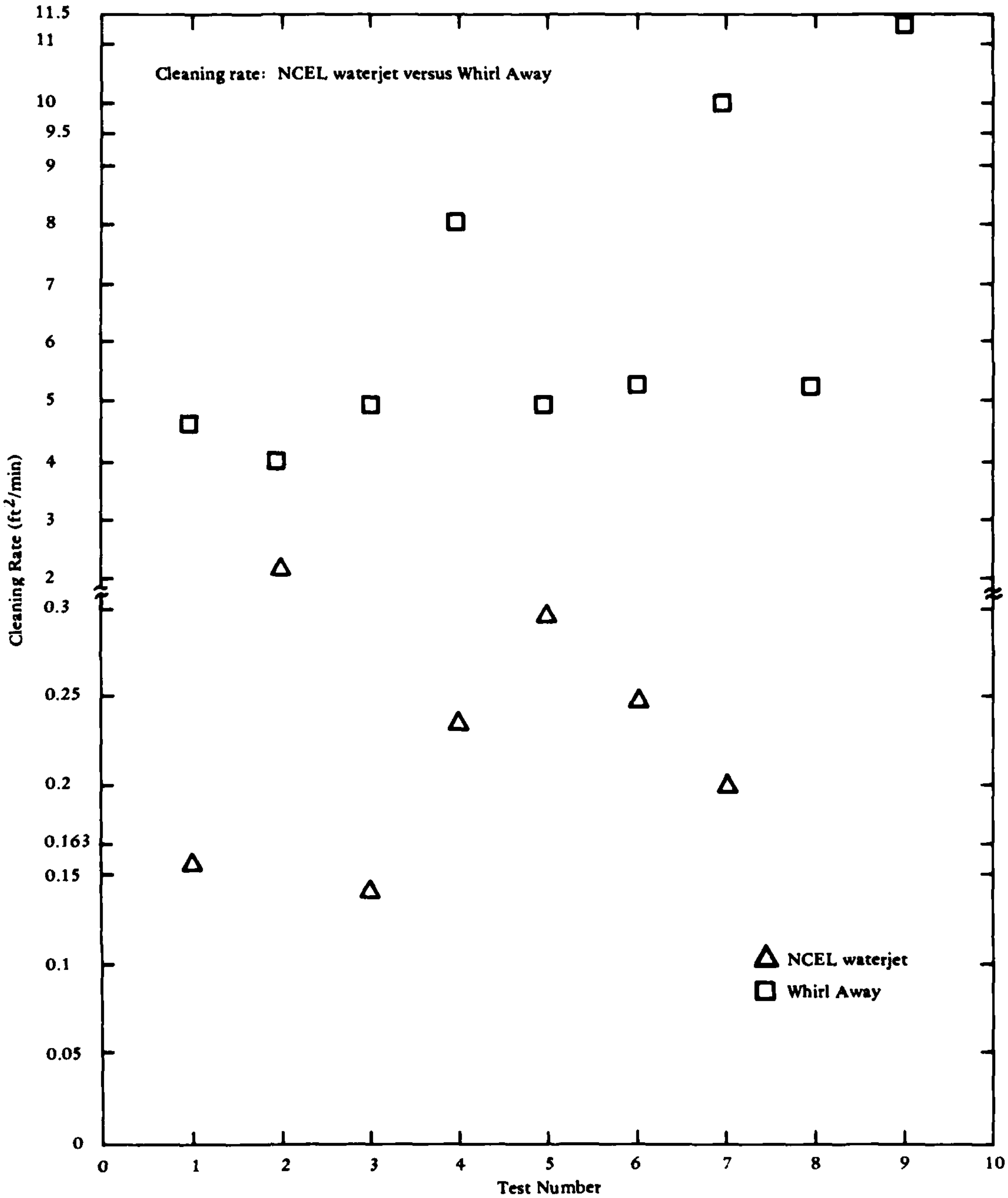


Figure 16. Whirl Away cleaning tests.

Table 10. Spring 1983 Cleaning Test Results Summary

Tool	Steel Cleaning Rate (ft^2/min)	Concrete Cleaning Rate (ft^2/min)
0.025-in. fan jet	2.41	a
0.031-in. fan jet	3.27	0.22
0.039-in. fan jet	2.52	0.25
0.031-in. straight jet	8.40	0.76
Whirl Away Hydraulic Tool	b	6.52

[a]This 0.025-in. fan jet nozzle could not achieve an acceptably clean final surface condition in a reasonable amount of time.

[b]Cleaning tests conducted in 1980 showed that the Whirl Away achieved an average cleaning rate of 2.45 ft^2/min on steel piles.

Seawater Cleaning Tests

The ability of the cleaning system to operate on seawater was evaluated during the high-pressure waterjet cleaning tests. A sump pump was used to draw seawater directly from the ocean. The seawater was filtered, pressurized, and then used to clean concrete and steel pilings in Port Hueneme Harbor. The cleaning system was also operated on seawater during the sound pressure level tests at Anacapa Island and in Port Hueneme Harbor.

The cleaning system operated well on seawater. No operational problems were encountered. Using seawater directly from the ocean greatly simplifies the operation by reducing the setup and cleanup time required to run lines to a freshwater supply. It also allows diving operations to be conducted from a vessel and in remote areas where freshwater is not readily available. However, after using seawater in the power source the system should be flushed thoroughly with freshwater to retard corrosion and increase the life of the hardware.

Sound Pressure Level Tests

Waterjet. Since the sound pressure level test data had been analyzed using the initial NEDU criteria, the time limit results reported for the prototype cleaning system were invalidated. Also, sound level measurements were made only on the largest nozzles, the 0.039-inch fan jet and 0.031-inch straight jet. Tests were not conducted on the smaller nozzles, since the two nozzles had the highest sound levels and resulted in no exposure time limits with a wetsuit hood (Ref 4). Once the new interim guidance was established, it became apparent that a time limit should be imposed on the larger nozzles since the correction for attenuation of noise by a wetsuit hood was no longer allowed.

In light of the new procedure for determining permissible exposure times, another series of sound pressure level measurement tests was planned. These tests were conducted by NCEL, after consulting with NCSC technical representatives, in a relatively quiet acoustic environment near Anacapa Island in April 1983. The sound pressure level produced by the cavitating waterjet pistol was measured at the diver's ear and 6 feet horizontally from the tool. Each of the measurements was made with one diver operating the tool and another diver holding a hydrophone at the proper location. Measurements were made while the tool was directed against a steel plate and while directed into open water. These four tests were conducted for each of the four available nozzles.

In addition to the tests made at Anacapa Island, sound level measurements were taken in Port Hueneme Harbor, Calif. These tests were made using the largest nozzle (0.039-inch fan jet) against concrete and steel pilings. The harbor tests were conducted to obtain sound levels from a realistic work environment. Table 11 lists all the sound level tests that have been conducted.

Table 11. NCEL Cleaning System Exposure Time Limits

Test	Distance From Diver's Ear (ft)	Direction of Tool	Time Limit (hr:min)
0.031-in. Straight Jet Nozzle			
NCEL-1[a]	0	against plate	5:46
NCEL-2		against plate	1:23
NCSC-1[b]		against plate	1:00
NCSC-33		against plate	5:59
NCEL-4		free stream	1:31
NCEL-5		free stream	3:23
NCEL-3	6	against plate	1:00
NCSC-5		against plate	1:12
NCEL-6		free stream	4:11
NCEL-7		free stream	1:52
NCSC-35		free stream	1:57
0.025-in. Fan Jet Nozzle			
NCEL-8	0	against plate	8:00
NCEL-9		against plate	13:30
NCEL-12		free stream	3:23
NCEL-13		free stream	7:28

continued

Table 11. Continued

Test	Distance From Diver's Ear (ft)	Direction of Tool	Time Limit (hr:min)
0.025-in. Fan Jet Nozzle (continued)			
NCEL-10	6	against plate	4:34
NCEL-11		against plate	6:57
NCEL-11		against plate	5:16
NCEL-14		free stream	2:41
0.031-in. Fan Jet Nozzle			
NCEL-19	0	against plate	1:58
NCEL-21		free stream	5:16
NCEL-20	6	against plate	1:34
NCEL-22		free stream	1:37
NCEL-22		free stream	1:18
0.039-in. Fan Jet Nozzle			
NCEL-15	0	against plate	8:56
NCEL-19		against plate	3:00
NCEL-21		free stream	6:16
NCSC-24		free stream	2:04
H5[c]		on concrete piling	2:13
H5		on concrete piling	4:06
H7		on steel H-piling	0:13
NCEL-16	6	against plate	3:20
NCSC-20		against plate	7:43
NCEL-18		free stream	3:04
NCSC-26		free stream	2:02
H6	6	on concrete piling	0:33
H8		on steel H-piling	1:18
H8		on steel H-piling	1:06
Whirl Away			
H1	0	on concrete piling	48:33
H3		on steel H-piling	10:24
H2	6	on concrete piling	16:00
H4		on steel H-piling	19:24

[a]These tests were conducted at Anacapa Island, Calif.

[b]These tests were conducted at Panama City, Fla.

[c]These tests were conducted at Port Hueneme Harbor, Calif.

The measurement instrumentation included a Bruel and Kjaer Model 8101 hydrophone (sensitivity: -184 decibels reference 1 V/μPa; frequency range: >1 Hertz to 80 kHz) to measure underwater noise and a Honeywell Model 101 magnetic tape recorder to record the sound levels. The data analysis was performed by NCSC to obtain the octave band levels of the recorded noise spectrums from 125 to 8,000 Hertz. An example that applies BUMED's interim guidance on the resulting octave band levels can be found in Appendix A.

The resulting exposure time limits based upon the sound pressure level tests conducted in April 1983 are as follows:

Nozzle	Time Limit (hr:min)
0.025-in. fan jet	6:27
0.031-in. fan jet	2:20
0.039-in. fan jet	3:16
0.031-in. straight jet	2:39

These exposure time limits are based upon an 8-hour day. The diver should use the smallest and quietest nozzle that can effectively clean the underwater structure for maximum diver safety and cleaning efficiency.

Whirl Away. During the harbor field evaluation of the prototype cleaning system, the divers commented that the Whirl Away hydraulic tool seemed excessively loud underwater. Therefore, after completing the sound pressure level tests on the high-pressure waterjet, a series of tests was conducted to evaluate the noise level produced by the Whirl Away hydraulic device.

The Whirl Away sound pressure level tests were conducted in Port Hueneme Harbor using the same instrumentation as during the waterjet noise measurements. The noise level measurements were made at the diver's ear and 6 feet away from the tool while cleaning both concrete and steel piling.

The sound level recordings were analyzed using the interim guidance provided by the Bureau of Medicine and Surgery as described in the Sound Pressure Level Tests section earlier. The allowable exposure times for divers operating the Whirl Away are all above 8 hours (Table 11). Since the time limit calculation is based on an 8-hour day, there is no operational time limit for the Whirl Away tool.

INTEGRATED LOGISTICS SUPPORT

Integrated logistics support (ILS) is a management function that assures that a system can be economically supported when placed in its operational environment. ILS involves maintainability, reliability, spares provisioning, human factors, personnel and training, and technical documentation.

Maintainability And Reliability

A measurement of maintainability is the Mean Time to Repair (MTTR), which is the arithmetic mean of the individual repair times. That is, MTTR is the summation of individual repair times during a given period of time divided by the total number of repairs during that time interval (Ref 7). During the test and evaluation of the prototype cleaning system, a record was kept of all the malfunctions and required repairs. Also, the development contractor, Flow Industries, Inc., was asked to provide maintainability data based upon similar power units they manufacture. Based upon these sources of information, the MTTR calculated for the prototype waterjet cleaning system was 0.33 hour or approximately 20 minutes.

Also, as part of the contract development of the prototype system, the manufacturer was asked to supply a recommended maintenance schedule. Detailed maintenance and repair instructions are provided in a Technical Manual (Ref 8). Reference 8 includes information on functional description, system operation, and maintenance and service. Routine maintenance, corrective maintenance, and shop maintenance and repair are described in detail.

A measurement of reliability is the Mean Time Between Failures (MTBF). The MTBF is the average length of time that the system will function normally under typical operating conditions. It is the inverse of the failure rate, where the failure rate is the number of failures of the system per hour of operation. The MTBF does not take into consideration factors such as preventative maintenance, human error, or quality of workmanship. Rather the MTBF is is based upon the anticipated failures due solely to the inherent characteristics of the system design (Ref 7). The MTBF for the prototype cleaning system was based upon the failure rate during the 2 years of test, evaluation, and modification at NCEL after delivery of the system. The MTBF for the prototype was determined to be 19 hours. This value should significantly increase with future cleaning systems since this is based on a prototype system.

From the MTBF and the MTTR, the inherent availability of the system can be determined. The inherent availability is defined as:

> The probability that a system or equipment, when used under stated conditions, without consideration for any scheduled or preventative action, in an ideal support environment (i.e., available tools, spares, manpower, data, etc.) shall operate satisfactorily at a given point in time. It excludes ready time, preventative-maintenance downtime, logistics time, and waiting or administrative downtime. (Ref 7)

The inherent availability is expressed as the following,

$$A = MTBF/(MTBF + MTTR)$$

The calculated inherent availability of the prototype cleaning system is 0.9829. This value will increase with future systems since the MTBF and MTTR are based upon the failure rate of a prototype system.

Spares Provisioning

At the end of the system development the prototype contractor listed the types and quantities of spare parts that might be needed. Based upon the field evaluation and system modifications, the spare parts requirements were updated and a spare parts list was developed. This list (see Ref 8) includes items such as filters, switches, and gages.

Human Factors

Human factors have been considered throughout the development of the prototype cleaning system. Items such as safety, accessibility, ease of use, packaging, handling, and panel displays and controls were all considered in the design, test, and modification stages of the prototype system development. Items such as the blow-out disk, automatic trigger locking mechanism, and on/off foot valve were incorporated into the cleaning system to improve overall safety. Other safety items include a set of automatic shutdown switches that are activated if an excessively high hydraulic temperature, low inlet water pressure, or low oil pressure occurs. Whenever an automatic shutdown occurs, a light located on the front control panel is illuminated, indicating the cause of the shutdown.

To improve accessibility, removable panels are located on the exterior of the power unit. The panels can be completely removed to allow easy access for maintenance and repair operations on any of the modules in the power source. Since the system is packaged in modules that can be removed individually, routine maintenance and major overhauls are improved. To improve handling and transporting the cleaning system, the modules are bolted together in a skid-mounted frame that has been designed for overhead crane and forklift handling.

Controls, gages, and indicator lights are all located on one side of the power source. Gages, including inlet water pressure, hydraulic system pressure, and intensifier inlet pressure, are located on a control panel with the water pressure adjustment control and bleed valve. On the face of the nearby electrical panel are seven gages, six warning lights, and a row of switches. The seven gages indicate engine speed (tachometer), system voltage (voltmeter) and current (ammeter), fuel level, diesel engine head temperature, cumulative hours of system operation, and diesel engine oil pressure. The warning lights indicate a broken drive belt for the alternator, high head temperature on the engine, low engine oil pressure, high hydraulic oil system pressure, low pump servo pressure, and low inlet water pressure. All the controls and displays are easily accessible and have been clearly labelled.

Personnel And Training

Personnel and training requirements have been minimized by maximizing standardization and using commercially available components wherever possible. An initial orientation to the operation, maintenance, and repair of the cleaning system is required to ensure proper usage and operator safety. Three operators are required to use the system as designed: a power source operator, a foot valve operator (usually the diving supervisor or tender), and the cleaning tool operator.

Technical Documentation

Technical data on the prototype cleaning system are primarily available from two sources: this Technical Report and the Technical Manual (Ref 8), which includes detailed drawings, operating and maintenance instructions, and other technical reference data. Other technical information on the prototype cleaning system can be found in Reference 2 and directly from the manufacturers of the various commercially available components included in the cleaning system.

SUMMARY AND CONCLUSIONS

In 1979 a series of tests was conducted to evaluate commercially available underwater surface cleaning systems. Based upon results of those tests, a prototype underwater cleaning system was developed by Flow Industries, Inc. under contract to NCEL. The prototype system incorporated the best features identified during the commercial cleaning systems evaluation. The NCEL prototype system included a small, handheld waterjet pistol; interchangeable cavitating fan and straight jet nozzles; a pilot-operated trigger valve with automatic safety lock; flexible, small-diameter, high-pressure supply hoses; a foot-actuated shutoff valve; and a diesel-driven power source. The power source delivers up to 5 gpm at 12,000 psi and includes a double-acting pressure intensifier and variable-displacement hydraulic pump.

The prototype system was evaluated during a series of laboratory and field tests in 1982. Based upon the results of those tests and on feedback obtained from the operators and test personnel, the prototype was modified to improve safety, ease of use, and overall performance in 1983. The modifications also allowed the system to operate on either freshwater or seawater and to power hydraulically driven tools. During the field tests on the prototype cleaning system, it was determined that the high-pressure waterblaster was best suited for cleaning steel underwater structures, particularly in limited access areas. On concrete underwater structures, the best cleaning device was found to be the Whirl Away rotary abrading hydraulic tool, which is manufactured by R.C. Collins Co. Both concrete and steel underwater structures can be effectively and efficiently cleaned using the NCEL system, since one power source can drive both the Whirl Away hydraulic tool and the NCEL waterjet pistol.

During 1983, after the final performance tests were completed on the modified prototype, documentation was submitted to obtain Authorization for Navy Use. A Technical Manual (Ref 8) containing detailed operation and maintenance instructions was written along with a set of procurement specifications for procuring production cleaning systems based upon the final modified prototype developed by NCEL.

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Appendix A

SOUND PRESSURE LEVEL CALCULATIONS

INTERIM GUIDANCE

In July 1982, the Bureau of Medicine and Surgery (BUMED) provided interim guidance for determining underwater noise levels that superceded the existing method of calculating exposure time limits for underwater operators. The interim guidance is in effect while BUMED completes a study and develops a comprehensive instruction on underwater noise limits. The interim guidance is as follows:

a. Continue to use standard techniques and instrumentation developed by the underwater sound community and to thoroughly document each test and evaluation of underwater tools and equipment.

b. Recompute the correction factor for impedance mismatch deleting the A-weighting factor. Perform the following steps for each test:

   (1) Obtain octave band levels of noise spectrum from 125 to 8,000 Hertz.

   (2) Subtract underwater hearing threshold levels at each octave frequency.

   (3) Add minimum audible field values for threshold in air.

   (4) Use combined octave band levels to compute allowable exposure time.

c. Use the Department of Defense criterion of 84 decibels for 8-hour exposure periods with a 4-decibel trading relationship for computing allowable exposure time.

d. Add equivalent noise dose in water to noise dose in air to obtain total daily noise dose for exposed personnel.

e. Do NOT use correction factors for attenuation of noise by wetsuit hood or the ear canal filled with water.

f. For noise with the preponderance of energy outside the frequency range of 125 to 8,000 Hertz or for impulse noise, consult with the Auditory Research Department, Naval Submarine Research Laboratory, New London, Conn.

g. Conduct annual monitoring hearing tests on exposed personnel.

SAMPLE CALCULATION

An average sound pressure level spectrum for the Naval Civil Engineering Laboratory (NCEL) prototype high-pressure waterjet tool (0.031-inch straight jet nozzle) is shown in Figure A-1. A worksheet used to calculate the permissible exposure time limits is shown in Figure A-2. Across the top of the worksheet are center frequencies of the octave band levels (OBLs) from 125 to 8,000 Hertz. Vertically, along the left side of the worksheet, are numbered steps for the calculation procedure.

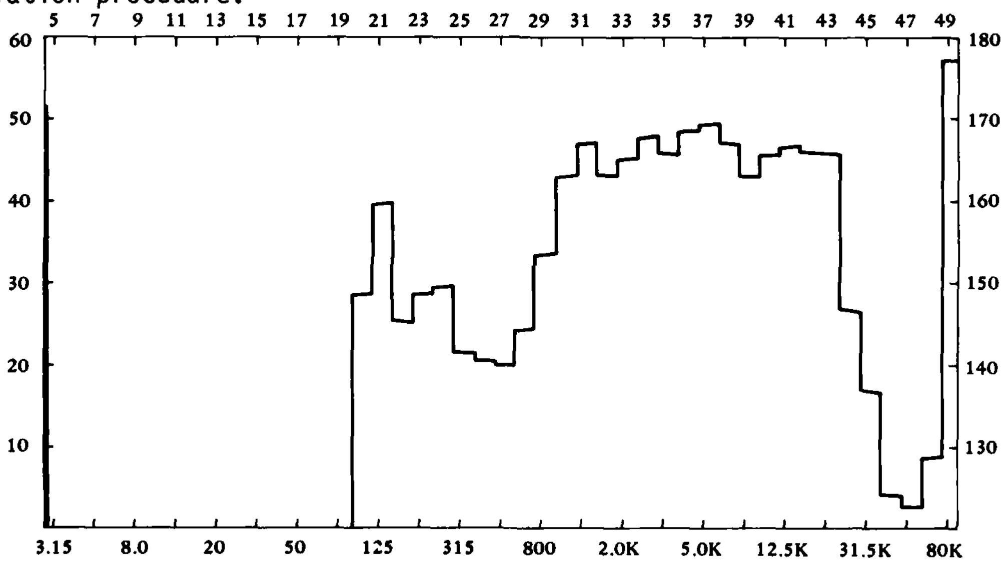

Figure A-1. Representative sound pressure level spectrum for the 0.031-inch straight jet nozzle in open water measured at the diver's ear.

In Step 1 the octave band levels of the noise spectrum (Figure A-1) are computed from the three corresponding one-third octave band levels labeled L_i. The octave band level is obtained from the equation:

$$L_{OBL} = 10 \log_{10} \left(\sum 10^{L_i/10} \right)$$

If an octave band analysis of the noise spectrum is used instead of a one-third octave band analysis, Step 1 is unnecessary and the octave band level can be read directly from the spectrum and entered as L_{OBL} on the worksheet.

Run #: ____________ Nozzle: ____________

Test Description: ____________

Step	Center Frequency	Frequency (Hz)						
		125	250	500	1,000	2,000	4,000	8,000
1	1 2 3							
2	L_{OBL} $- dB_{ref}$	-26.0	-26.0	-26.0	-26.0	-26.0	-26.0	-26.0
3	-u/w correct	-70.0	-65.0	-58.0	-60.0	-66.0	-67.0	-74.0
4	BSL + MAF	+21.0	+11.0	+6.0	+4.0	+1.0	-3.0	+10.0
	$L_i =$							
5	$L_c = 10 \log_{10} \left(\sum 10^{L_i/10} \right)$							
6	$T = 16 \div 2^{(L_c - 80)/4}$							

where: L_{OBL} = octave band level

dB_{ref} = correction to be in dB re 20 μPa

u/w correct = underwater heating threshold correction

BSL = band sensation level

MAF = minimum audible field thresholds in air

L_i = octave band level for equivalent air exposure

L_c = overall or combined exposure level

T = permissible exposure time in hours

Figure A-2. Sound pressure level permissible exposure time worksheet.

In Step 2 the OBLs are adjusted, if necessary, to be in decibels reference 20 μPa (db re 20 μPa). The adjustment, called decibels reference, requires subtracting 26 decibels from the OBLs in db ref 1 μPa.

In Step 3 underwater hearing threshold levels are subtracted from each octave band level (re 20 μPa). These threshold levels are as follows (Ref 9):

- 70 decibels for 125 Hertz
- 65 decibels for 250 Hertz
- 58 decibels for 500 Hertz
- 60 decibels for 1,000 Hertz
- 66 decibels for 2,000 Hertz
- 67 decibels for 4,000 Hertz
- 74 decibels for 8,000 Hertz

The result, after subtracting the underwater threshold from the octave band level, is the band sensation level (BSL).

In Step 4 the minimum audible field (MAF) threshold levels in air are added to the BSLs at each center frequency. The in-air MAF threshold levels are as follows (Ref 10):

- 21 decibels for 125 Hertz
- 11 decibels for 250 Hertz
- 6 decibels for 500 Hertz
- 4 decibels for 1,000 Hertz
- 1 decibels for 2,000 Hertz
- -3 decibels for 4,000 Hertz
- 10 decibels for 8,000 Hertz

The result, after subtracting the MAF threshold levels from the BSL, represents the octave band level for an equivalent exposure in air (L_i).

In Step 5 an overall or combined exposure level, L_c, is computed using the formula:

$$L_c = 10 \log_{10} \left(\sum 10^{L_i/10} \right)$$

where the L_i values are the octave band levels obtained in Step 4.

In Step 6 the permissible exposure time is calculated using the formula:

$$T = 16/2^{(L_c-80)/4}$$

where L_c is the combined or overall exposure level obtained in Step 5. The permissible exposure time, T, is expressed in hours. Figure A-3 shows the sound pressure level worksheet filled in based upon the noise spectrum in Figure A-1.

Run #: Anacapa #5 Nozzle: 0.031-inch straight jet

Test Description: in open water (free stream) measured at the diver's ear

Step	Center Frequency	Frequency (Hz)						
		125	250	500	1,000	2,000	4,000	8,000
1	1	148.5	148.5	140.5	153.5	163.0	165.5	167.0
	2	160.0	149.5	140.0	163.0	165.0	168.5	163.0
	3	145.0	141.5	144.0	167.0	167.5	169.0	165.5
2	L_{OBL}	160.4	152.4	146.7	168.6	170.3	172.7	170.2
	$-dB_{ref}$	-26.0	-26.0	-26.0	-26.0	-26.0	-26.0	-26.0
3		134.3	126.4	120.7	142.6	144.3	146.7	144.2
	-u/w correct	-70.0	-65.0	-58.0	-60.0	-66.0	-67.0	-74.0
4	BSL	64.4	61.4	62.7	82.6	78.3	79.7	70.2
	+ MAF	+21.0	+11.0	+6.0	+4.0	+1.0	-3.0	+10.0
	L_i =	85.4	72.4	68.7	86.6	79.3	76.7	80.2
5	$L_c = 10 \log_{10} \left(\sum 10^{L_i/10} \right) = 90.3$							
6	$T = 16 \div 2^{(L_c - 80)/4}$ = 2 hr, 40 min							

where:

L_{OBL} = octave band level

dB_{ref} = correction to be in dB re 20 μPa

u/w correct = underwater heating threshold correction

BSL = band sensation level

MAF = minimum audible field thresholds in air

L_i = octave band level for equivalent air exposure

L_c = overall or combined exposure level

T = permissible exposure time in hours

Figure A-3. Completed worksheet.

Appendix B

FIELD TEST QUESTIONNAIRE RESPONSES

This appendix presents the feedback obtained from test personnel during the field tests and evaluation of the NCEL prototype cleaning system. Test personnel were required to complete a questionnaire after operating the prototype tool. The questionnaire was used to obtain information on the cleaning capability, safety, and ease of use of the NCEL cleaning system. Information on diver experience and descriptions of the type of structure and amount of fouling cleaned were recorded. Also, recommendations to improve the cleaning ability, safety, or handling of the tool were documented. A typical completed questionnaire is shown in Figure B-1. Tables B-1 and B-2 summarize all the comments recorded on the questionnaires during testing by the Underwater Construction Team Two (UCT-2) in 1982 and by NCEL divers in 1983, respectively.

Figure B-2 shows the Daily Data and Critique Sheets obtained from the UCT-2 field evaluation at Subic Bay, RP, in August 1982. The critique sheets were used to record any maintenance performed or repairs required during the testing. Also, any operational or safety problems encountered were explained.

INDIVIDUAL'S QUESTIONNAIRE FOR JET-PAC HIGH PRESSURE WATERJET CLEANING SYSTEM

This questionnaire is to be completed once by all personnel associated with the on-site testing of the waterjet system after about one week of use. (Circle answers where appropriate)

1. Name (Last, First, Middle) MILLER DONALD JOSEPH
2. Rate/Rank: SW2/DV
3. Duty Address: UCT-2 PORT HUENEME CA 93043
4. Previous experience with other high pressure waterjet cleaning tools? 1. YES 2. NO
5. Previous experience with other underwater cleaning tools? 1. YES 2. NO
6. If answer to 4 or 5 was YES, specify which tools and how does this waterjet tool compare with them: PARTEK WATERBLASTER- CLEANING WAS @ THE SAME. THE CEL WATER JET IS ALOT LIGHTER HAS AN EASIER TRIGGER PULL AND ITS WATER SUPPLY HOSE IS EASIER TO MANIPULATE IN WATER. WHIRL AWAY-CLEANS CONCRETE BETTER THAN THE CEL WATER JET BUT IS BY FAR ALOT MORE CUMBERSON.

DURING THIS TEST:

7. Type of structure cleaned: 1. Concrete 2. Steel H Pile 3. Sheet Pile 4. Other (explain)
8. Type of fouling on the structures? (Circle as many as appropriate):
   1. Barnacles 2. Tubeworms 3. Mussels 4. Kelp 5. Rust 6. Scale 7. Slime 8. Coral 9. Other
9. Amount of fouling:
   1. Light (1") 2. Moderate (2") 3. Heavy (3" or more)

10. How did the waterjet tool clean?
    1. Excellent - Cleaned to structure base surface quickly
    2. Good - Removed fouling agent(s) generally to base surface but required time
    3. Poor - Did not do the job effectively or efficiently
11. Did you feel any effects from the underwater noise? 1. YES 2. NO
    If YES, please explain:
12. Did you feel any hand or arm fatigue? 1. YES 2. NO
13. How long did you operate the tool each dive? 80 min
14. Were any operating, safety or handling problems encountered or noted regarding the:

High pressure hose	1. YES	2. NO
Waterjet pistol	1. YES	2. NO
Power source	1. YES	2. NO
Foot valve	1. YES	2. NO

15. If you answered YES to any of the above, please explain:
16. Do you have any recommendations to improve the cleaning ability, safety, or handling of the waterjet tool? 1. YES 2. NO
    If YES, please explain: I think A shoulder stock would BE MOST HELPFUL AND A VERTICAL GRIP RISING OFF the TOP OF THE GUN OR HORIZONTALLY FROM THE SIDE OF THE BODY WOULD HELP IN GUN STABILITY.

Figure B-1. Completed questionnaire.

DAILY DATA AND CRITIQUE SHEET FOR JET-PAC HIGH PRESSURE WATERJET CLEANING SYSTEM

Chief Petty Officer-in-Charge complete this data sheet each day of cleaning tests.

1. Date: 17 AUG 82

2. Engine Hour Meter (start): 105.1   Fuel Level (start): 7/8

   Engine Hour Meter (finish): 108.5   Fuel Level (finish): 3/4

3.

Waterjet Operators Name (Last, First, Rate)	Minutes Operated	Nozzles S.031	F.025	F.031	F.039	Operating Pressure	Operating Flow Rate
MILLER DEN [illegible]	:25				✓	10,000 PSI	4.5 GPM
[illegible]	:25				✓	10,000 PSI	4.5 GPM
Little Jeff [illegible]	:55	✓				10,000 PSI	2-3 GPM
[illegible]	:55	✓				10,000 PSI	2-3 GPM

4. Maintenance Performed: (circle and explain, if necessary)

1a Water System   1b Filters
2a Hydraulic System   2b Fluid
3a Diesel Engine   3b Oil
4 Hand-held Cleaning Tool
5 Foot Valve

4 TRIGGER LOCK JAMMED IN THE OPEN POSITION. JAMMING DUE TO DIVER UNFAMILIARITY WITH THE PISTOL AND USEING UNNECESSARY FORCE TO OPERATE THE TRIGGER.

1a REPLACED BLOWN O-RING IN FORWARD INTENSIFIER CYLINDER OUTLET.

5. Operating, Safety or Handling Problems Encountered: (circle and explain)

(1) High Pressure Hose
(2) Waterjet Pistol
(3) Power Source
(4) Foot Valve

2 TRIGGER SAFETY JAMMED DUE TO OPERATOR USING EXCESSIVE FORCE

6. Repairs Attempted or Completed: (circle and explain)

(1) Filter Elements
(2) Switches
(3) Gauges
(4) Seals
(5) Nozzles
(6) Valve Body

4 O-RING IN FORWARD INTENSIFIER CYLINDER OUTLET

7. Total Number of Pilings Cleaned: 1

8. Do you have any recommendations to improve the cleaning ability, safety, or handling of the waterjet tool? (1) YES (2) NO

If YES, please specify:

DAILY DATA AND CRITIQUE SHEET FOR JET-PAC HIGH PRESSURE WATERJET CLEANING SYSTEM

Chief Petty Officer-in-Charge complete this data sheet each day of cleaning tests.

1. Date: 8/16/82

2. Engine Hour Meter (start): 103.2   Fuel Level (start): 1/2

   Engine Hour Meter (finish): 105.1   Fuel Level (finish): 3/8

3.

Waterjet Operators Name (Last, First, Rate)	Minutes Operated	Nozzles S.031	F.025	F.031	F.039	Operating Pressure	Operating Flow Rate
Revell Ken [illegible]	:25	✓				10,000	3 GPM
Revell Ken [illegible]	:40				✓	10,050	4.5 GPM

4. Maintenance Performed: (circle and explain, if necessary)

1a Water System   1b Filters
2a Hydraulic System   2b Fluid
3a Diesel Engine   3b Oil
4 Hand-held Cleaning Tool
5 Foot Valve

5. Operating, Safety or Handling Problems Encountered: (circle and explain)

(1) High Pressure Hose
(2) Waterjet Pistol
(3) Power Source
(4) Foot Valve

6. Repairs Attempted or Completed: (circle and explain)

(1) Filter Elements
(2) Switches
(3) Gauges
(4) Seals
(5) Nozzles
(6) Valve Body

Unit Kicked Off Due To High Temp Hydraulic Alarm Temp Switch Defective Max Oil Temp 180° F.

7. Total Number of Pilings Cleaned: 1 (17') 4 sided 18" x 18" 102 SF

8. Do you have any recommendations to improve the cleaning ability, safety, or handling of the waterjet tool? (1) YES (2) NO

If YES, please specify:

Figure B-2. Daily Data and Critique Sheets.

Table B-1. UCT-2 Field Test Questionnaire Summary Sheet for Concrete Pilings[a] at Subic Bay, RP, August 1982

Personnel	Previous Experience With Waterjets	Previous Experience With Hydraulic Cleaning Tools	Comparison of NCEL's Tool With Previously Used Tools	Cleaning Effectiveness	Effects From Noise	Operating Time (min)	Hand/Arm Fatigue	Safety, Operating, or Handling Problems With-- High-Pressure Hose	Pistol	Power Source	Foot Valve	Explanation of Problems	Recommendations
SW2/DV	yes Partek	yes Whirl Away	Cleaning was about the same as Partek. NCEL's tool is much lighter, has an easier trigger pull, and its water supply hose is easier to manipulate in water. The Whirl Away cleans concrete better but is by far a lot more cumbersome.	good	no	20	no	no	yes	no	no	The safety switch was not working properly and got jammed	
BU2/DV	yes Partek	yes Whirl Away	The Whirl Away is better because it can remove barnacles and mussels easily. The only drawback is that the Whirl Away is only effective on smooth, flat surfaces. Because it is not a flexible unit, it was much less effective in crevices (corners).	good	no	20-30	no	no	no	no	no		A shoulder stock or extension
EA3/DV	yes Partek	yes Whirl Away	The NCEL waterjet cleans as well as the Partek. One advantage of the NCEL tool is that the gun is smaller and lighter. For flat surfaces, the Whirl Away surpasses the waterjet.	good	no	30	no	no	no	no	no		A shoulder stock or a vertical grip
EO2/DV	no	yes Whirl Away	The Whirl Away is better at cleaning. The power source is nicer, simpler, and more modern to operate than the Partek.	good	no	65	yes	no	yes	yes	yes	• Needs shoulder stock • Replace O-ring in intensifier • Need direction arrow on foot valve	A vertical handle off the top or side to hold onto with free hand

[a] Piling was fouled with a moderate-to-heavy (2- to 3-in.) covering of barnacles, tubeworms, mussels, slime, coral, and scale.

Table B-2. Port Hueneme Harbor Field Test Questionnaire Summary Sheet, April 1983

Personnel	Previous Experience With Waterjets	Previous Experience With Hydraulic Cleaning Tools	Comparison of NCEL's Tool With Previously Used Tools	Cleaning Effectiveness	Effects From Noise	Operating Time (min)	Hand/ Arm Fatigue	Safety, Operating, or Handling Problems With--				Explanation of Problems	Recommendations	Comments
								High-Pressure Hose	Pistol	Power Source	Foot Valve			
0.039-in. Fan Jet on Steel H-Piling[a]														
BU2/DV	yes Daedalean	no	NCEL's tool is more powerful than Daedalean's	excellent	no	25	yes	no	no	no	no		Shoulder stock needs to be shortened/ strengthened; without stock back thrust is tiring (telescoping/adjust)	• Cleaned about 1-ft section with each pass • 0.039-in. fan jet nozzle cleans fastest but is most tiring • 0.025-in. fan jet nozzle is easiest to operate and maneuver but cleans more slowly
CUCM/MDV	no	no		excellent	no	15	no	no	no	no	no			
EO3/DV	yes Partek	yes		excellent	no	50	yes	no	yes	no	no	Needs a shoulder stock		
0.039-in. Fan Jet on Concrete Piling[b]														
EO3/DV	yes Partek	yes	NCEL's tool is by far superior; I have not used one as effective	good-fair	no	60	yes	no	yes	no	no	Needs a shoulder stock	Shoulder stock needs to be shortened/ strengthened; without stock back thrust is tiring (telescoping/adjust)	• Does not remove all shells from concrete or clean to the base material • Straight jet is better at cleaning than the fan jets
CMC/DV	yes Partek	yes		good-fair	no	30	no	no	no	no	no			
Whirl Away on Both Steel and Concrete Piling[b]														
BM1/Diver	yes hull cleaner	yes	N/A	excellent	yes	25	yes	N/A					Was heavy - could use a float or synthetic foam	• Faster and more efficient than waterblaster • It seemed louder than the waterjet underwater
LCDR	yes NAVSEA tool package	yes		good	yes	30	yes	N/A						

[a]Piling was fouled with a light-to-moderate (1- to 2-in.) covering of barnacles, tubeworms, scale, kelp, and slime.

[b]Piling was fouled with a moderate-to-heavy (2- to 3-in.) covering of barnacles, tubeworms, mussels, slime, scale, and kelp.

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